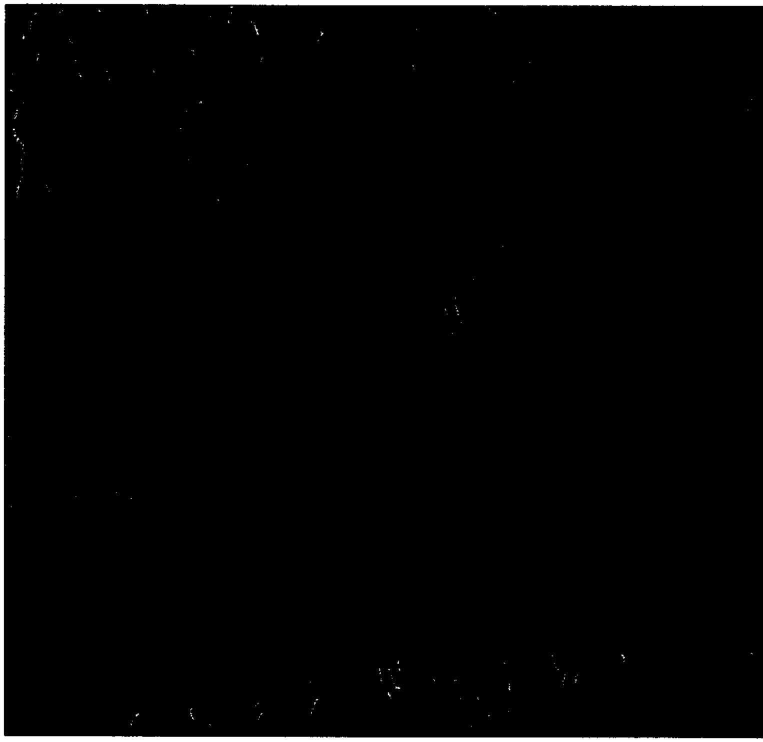
Vegetation Parameters using TOPSAR and GeoSAR Sensors

Scott Hensley, Ernesto Rodíguez, Paul Siqueira, Elaine Chapin,
Thierry Michel and Marc Simard

Jet Propulsion Laboratory
4800 Oak Grove Dr
Pasadena, California 91109

This paper will present quantitative results of vegetation parameter extraction using interferometric data collected using the TOPSAR and GeoSAR mapping instruments. These radars operate interferometrically over a range of frequencies from X-band to P-band. Radar data derived vegetation parameters are compared to LIDAR data and *in situ* measurements for a variety of canopy and terrain types. Comparison of how the different frequencies interact with the vegetation as a function of tree height, incidence angle and canopy parameters are presented.

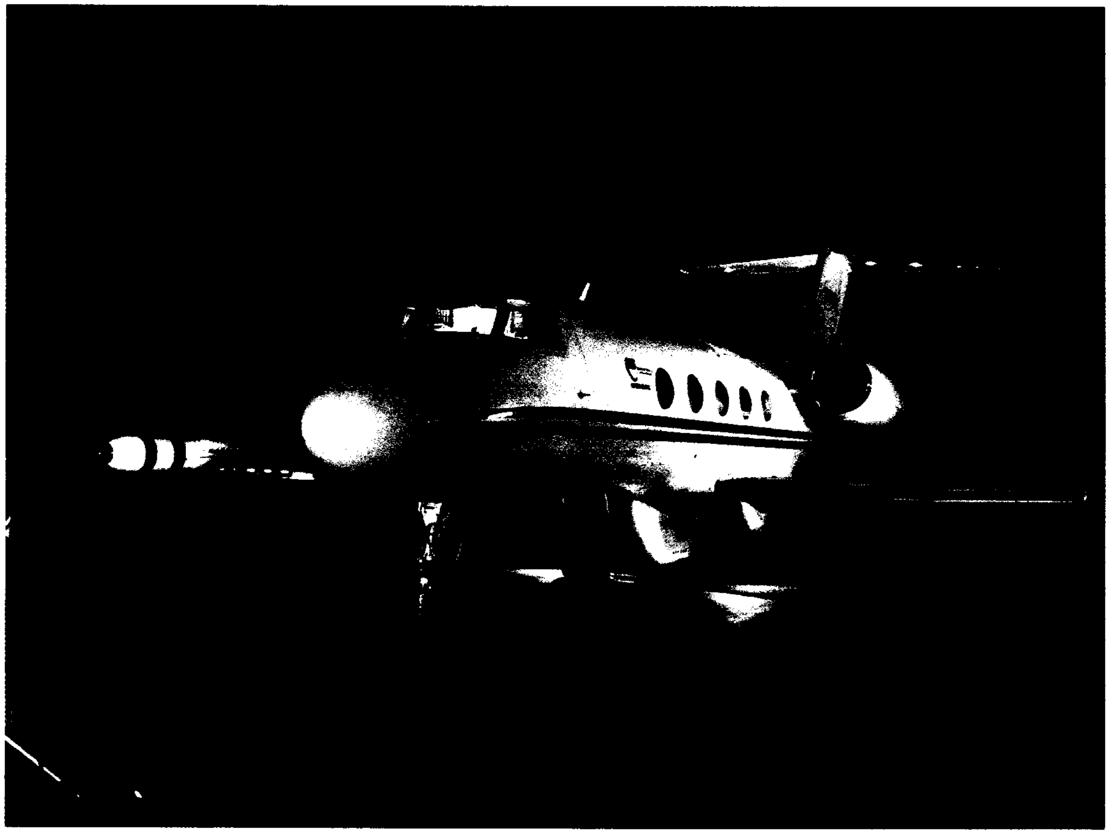
This research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.



Scott Hensley, Ernesto Rodríguez,
Paul Siqueira, Elaine Chapin,
Thierry Michel & Marc Simard

POLinSAR
January 14-16, 2003
Frascati, Italy

What is GeoSAR?



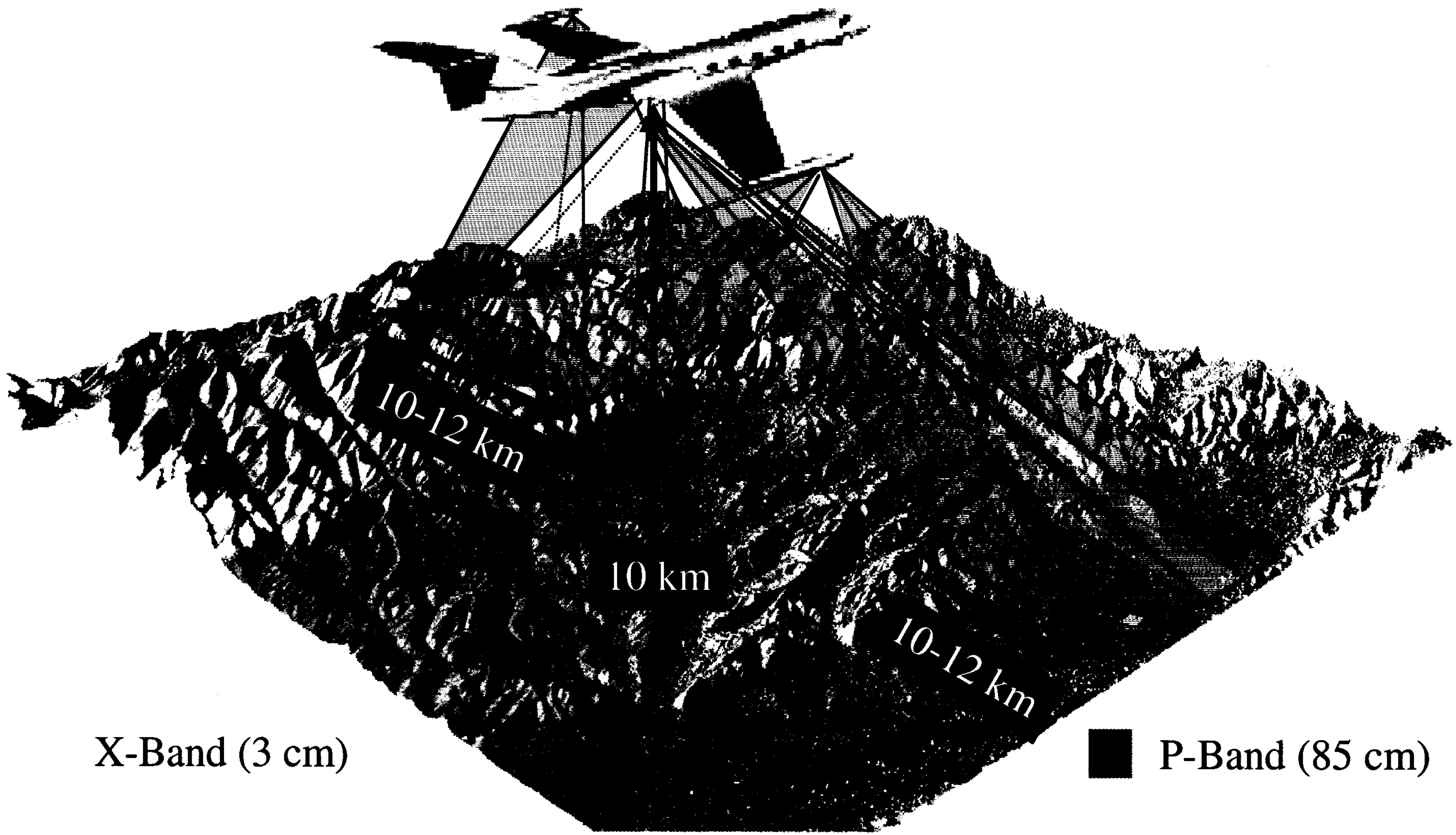
EarthData's modified Gulfstream-II jet

An interferometric airborne radar mapping system that uses two frequencies to generate digital elevation models (DEMs) and orthorectified radar reflectance maps near the tops of trees as well as beneath foliage.

Overview of GeoSAR

- Aircraft-based, interferometric synthetic aperture radar (SAR) system for topographic mapping.
  - Gulfstream II business jet
  - Day/night, all-weather, low-cost, commercial system
- Develop precision foliage penetration mapping technology based upon dual frequency, dual polarimetric, interferometric radar.
  - X-band radar (λ=3 cm) for bare ground and "tops" of trees
  - P-band (UHF) radar (λ=86 cm) for foliage penetration (HH,HV)
- Produce true ground surface digital elevation models suitable for a wide variety of applications.
- Program initially managed by DARPA, currently managed by NIMA
  - Caltech's Jet Propulsion Laboratory (JPL), Pasadena, CA
  - Earth Data International, Inc., Fresno, CA
  - California Department of Conservation (CalDOC)

GeoSAR Data Collection Geometry

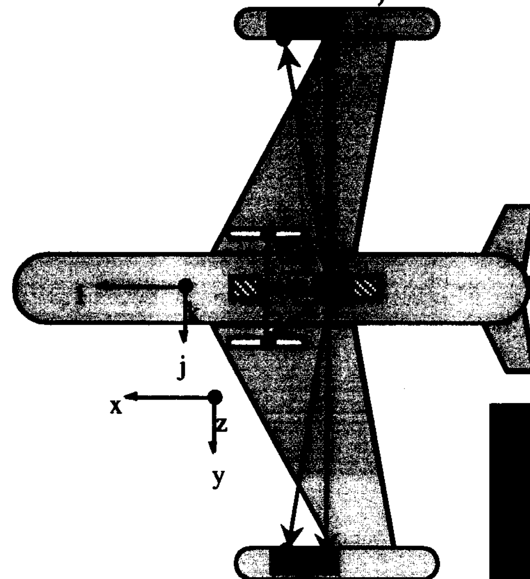


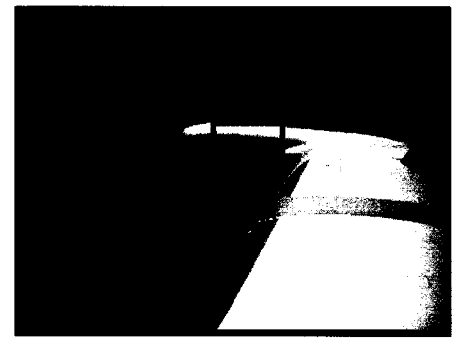
GeoSAR collects interferometric radar data simultaneously on the left and right side of the aircraft for both X-Band and P-Band. The combined data rate for the two radars is 1 Gb/s!

GeoSAR Radar System Overview

Radar is operated from the Radar operator workstation.

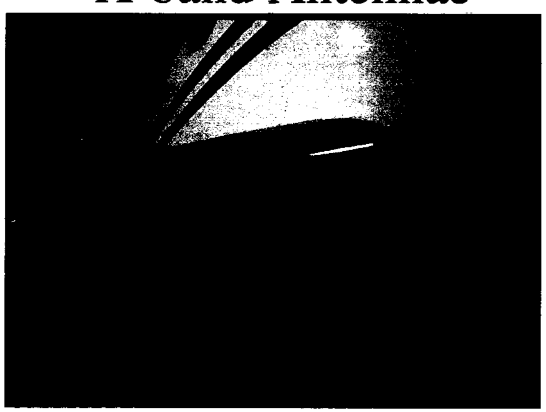
Aircraft, bottom view



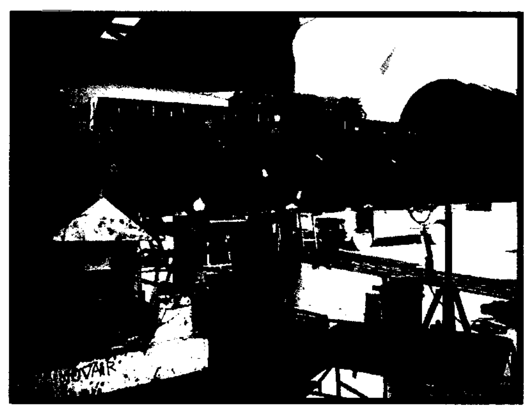


LBMS target array viewed in flight.

X-band Antennae



P-band Antennae



P-band antennas are cavity fed micro-strip arrays. Antennas are designed to operate with 160 MHz of bandwidth with a 350 MHz center frequency.

Interferometric Correlation

- The interferometric correlation for repeat pass systems can be written as the product of four terms

$$\gamma = \gamma_g \gamma_{snr} \gamma_v \gamma_t$$

where γ_g is the geometric correlation, γ_{snr} is the SNR correlation, γ_v is the volumetric correlation and γ_t is temporal decorrelation.

- The geometric correlation is a function of the baseline, surface slopes, how the signals are processed and the impulse response function. This term is measuring the amount of signal difference between the two antennas due to their physical separation and any "asymmetric" processing done to the two channels. By carefully tracking what is done to the signals in the processing this term can be computed and compensated.
- The SNR correlation measures the reduction in signal similarity due to thermal and other noise sources such as ISLR noise. By measuring or estimating the amount of thermal and other noise sources this term can be computed and estimated.
- The volumetric correlation is related to the vertical distribution of scatterers within a resolution element.

Volumetric Correlation

- Vegetation layers cause height biases and decorrelation of interferometric data. The amount of additional decorrelation caused by the canopy is given by

$$\gamma_v = \frac{\int \sigma(z) e^{-ik_z z} dz}{\int \sigma(z) dz}$$

where k_z is the projected wave number in the vertical direction and $\sigma(z)$ is the scatterer cross section (including attenuation) as a function of height.

- Unlike the SNR and geometric correlation terms that are "easily" computed given a few simple parameters that describe the system and processing environment the volumetric correlation can be computed only after assuming a functional form for the canopy and a model for how energy is scattered from the canopy.
- Real canopies are complex scattering environments not easily described by a simple function that can take into leaf and crown structure, gap structure, ground cover variations, etc..
- However, for certain simple canopy models closed form expressions for the the volumetric correlation can be obtained. These models are sometimes useful for developing a basic understanding of how volumetric correlation depends on canopy parameters although their simplicity precludes their use for a general canopy inversion algorithm.

Some Simple Models

- What is a simple model? A simple model for us will be ones for which a closed form expression for the volumetric correlation, γ_v, can be obtained.
- What we need are functions $\sigma(z)$ such that the integrals, I_N and I_D can be evaluated in closed form where

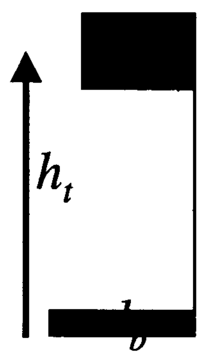
$$I_N = \int \sigma(z) e^{-ik_z z} dz \qquad I_D = \int \sigma(z) dz$$

<u>Three Simple Models</u>

Two Point Canopy

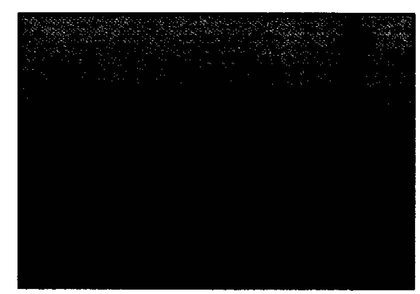
$$\frac{a_t}{a_t + a_b}\delta(z - h_t) + \frac{a_b}{a_t + a_b}\delta(z - h_b)$$

Two Box Canopy



$$\frac{a_t}{a_t + a_b} rect(d_t, h_t) + \frac{a_b}{a_t + a_b} rect(d_b, h_b)$$

Exponential Canopy



- To explore the effect of shape of canopy rect can be replaced by a cosine on a pedestal or a gaussian (if you allow erf functions) and the integrals can still be done in closed form.

Volumetric Correlation Formulas

$$\gamma_v = \frac{a_t}{a_t + a_b} e^{-ik_z h_t} + \frac{a_b}{a_t + a_b} e^{-ik_z h_b}$$

Two Point Canopy

If $a_t = a_b$ then

$$\gamma_v = e^{-ik_z (h_t + h_b)/2} \cos\left(\frac{k_z (h_t + h_b)}{2} \right)$$

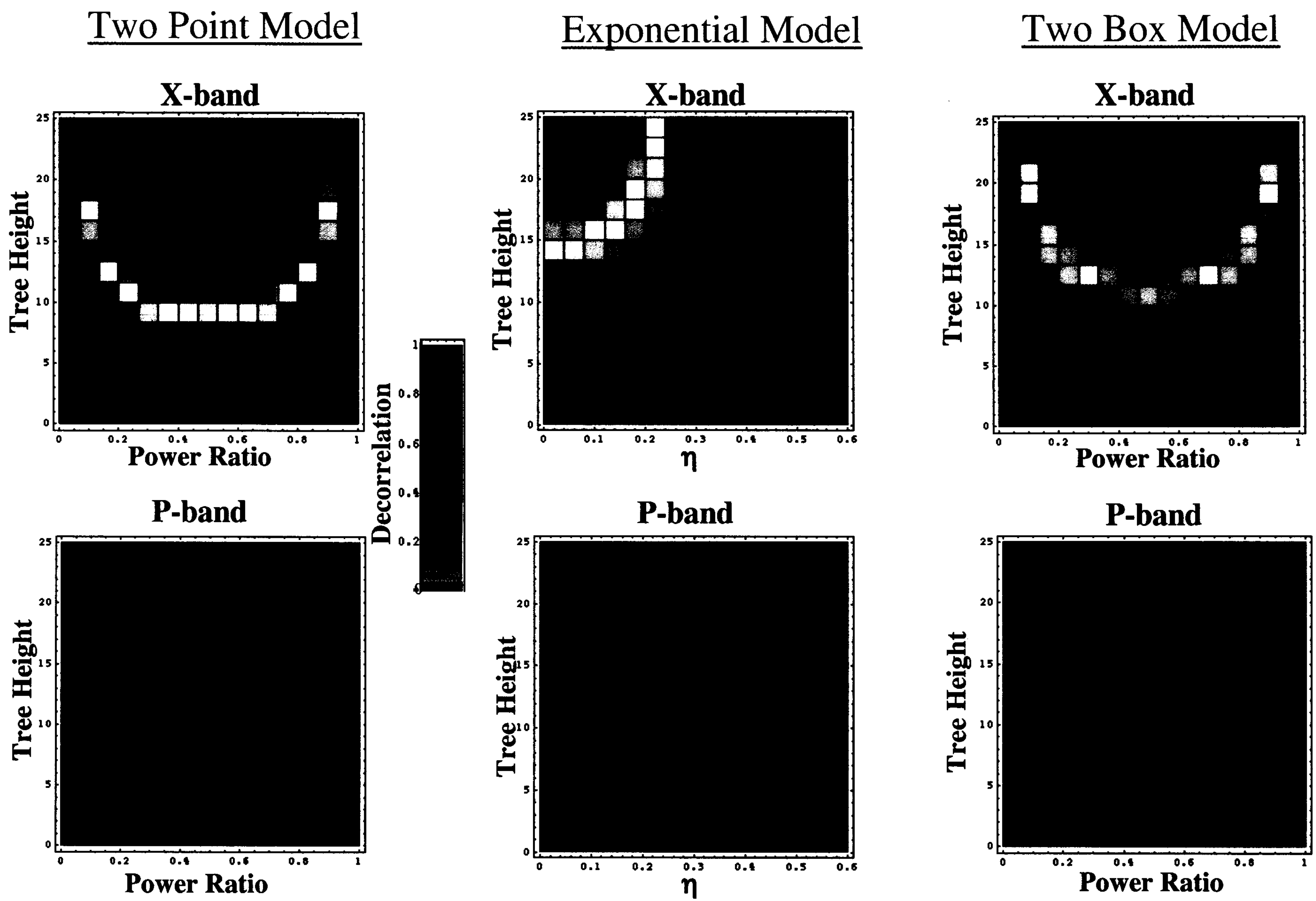
$$\gamma_v = \frac{2a_t}{a_t + a_b} \frac{e^{-ik_z h_t}}{d_t k_z} \sin\left(k_z \frac{d_t}{2} \right) + \frac{2a_b}{a_t + a_b} \frac{e^{-ik_z h_b}}{d_b k_z} \sin\left(k_z \frac{d_b}{2} \right)$$

Two Box Canopy

$$|\gamma_v| = \frac{\eta \left[\sinh^2\left(\frac{\eta h}{2}\right) \cos^2\left(\frac{k_z h}{2}\right) + \cosh^2\left(\frac{\eta h}{2}\right) \sin^2\left(\frac{k_z h}{2}\right) \right]^{\frac{1}{2}}}{\sqrt{\eta^2 + k_z^2}\, \sinh\left(\frac{\eta h}{2}\right)}$$

Exponential Canopy

Volumetric Decorrelation Examples



Interferometric Volume Scattering Review

- The interferometric phase for a given range cell varies as a function of height from the ground.
- In the presence of vegetation layers, this varying phase will lead to a height bias and increased decorrelation.
- The additional complex volumetric decorrelation caused by the canopy is

$$\gamma_z(\kappa_z) = \int e^{-i\kappa_z z} f(z)dz$$

where k_z is the wavenumber in the vertical direction.

- f(z) is the effective scattering cross section (including attenuation) as a function of height

$$f(z) = \frac{\sigma_0(z)}{\int \sigma_0(z)dz}$$

- The canopy is fully characterized when f(z) is inverted from the data

Cumulant Inversion Overview

•Since the vertical fringe wavelength is typically much larger than the tree height, one cannot invert the volumetric correlation integral using Fourier transforms.

•The relationship between f(z) and the volumetric decorrelation is identical to the one between a probability density function and its characteristic function: 0< f(z)<1 and the integral of f(z) is normalized to unity.

•It is well known that a pdf is most often best characterized by its cumulants, which are just the centered moments for the first few cumulants

$$\mu_1 = \langle z \rangle \qquad \textbf{Height bias}$$

$$\mu_2 = \left\langle \left(z - \langle z \rangle \right)^2 \right\rangle \qquad \textbf{Penetration Variance}$$

where

$$\left\langle z^n \right\rangle = \int z^n f(z) dz$$

•The cumulants are related to the volumetric decorrelation by

$$\gamma_z = \exp\left[\sum_{n=1}^{\infty} \frac{i^n}{n!} \mu_n \kappa_z^n \right]$$

Cumulant Inversion Overview

- Even the most simplified canopy model (e.g., exponential attenuation) has more parameters (e.g., canopy height and attenuation) than can be recovered from a single correlation measurement.

- Parametric inversions proceed by assuming values for all of the parameters but the canopy height, and inverting the resulting model. This requires a priori knowledge and will change between canopy types.

- The penetration standard deviation provides a non-parametric estimate of the amount of penetration into the canopy

  - Multiple C-band interferometric observations have shown that approximate tree height and height bias can be estimated using a simple scaling of this parameter for a variety of canopies.

  - The scaling constant for X-band and P-band is being investigated for GeoSAR

- Given the interferometric correlation measurement, the penetration standard deviation is given by

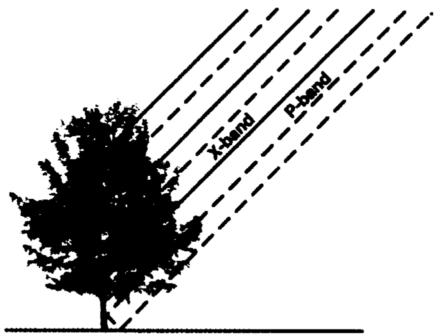
$$\sqrt{\mu_2} = \sqrt{-2\frac{\ln|\gamma| - \ln\gamma_g - \ln\gamma_N}{k_z^2}}$$

γ_g **Geometric correlation**

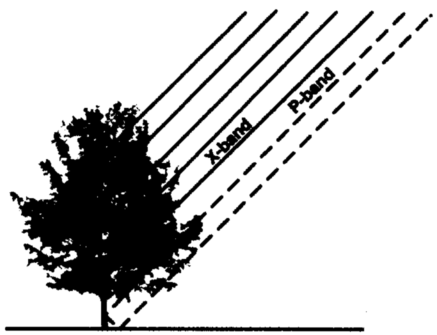
γ_N **Noise correlation**

$|\gamma|$ **Measured correlation**

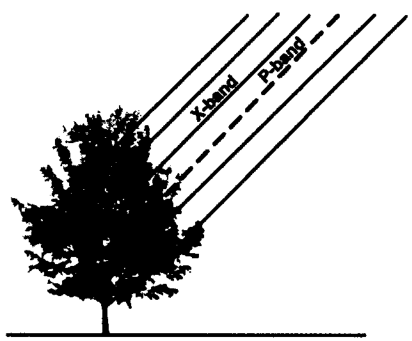
Scattering Mechanism Impact on Height Estimate



Mixed Scattering: P-band has contributions from the canopy and lower components, including double bounce. The X-band interacts predominantly with the canopy. P-band heights above the bare earth, but lower than X-band.



Double-Bounce Dominant: The P-band height estimate is close to the bare earth. The X-band estimate is in the canopy. The X-P height difference is almost identical to the X-band height bias.

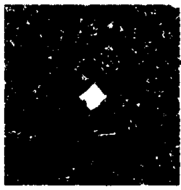


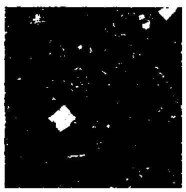
Canopy Dominant: The P-band interacts very strongly with a large canopy component. The contribution from double-bounce is small. The X-band height can be smaller than the P-band height.

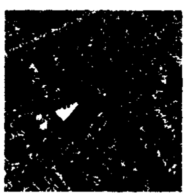
X-band Height Accuracy Assessment in Clear Areas

X–band Height Accuracy Assessment at Duke Forest

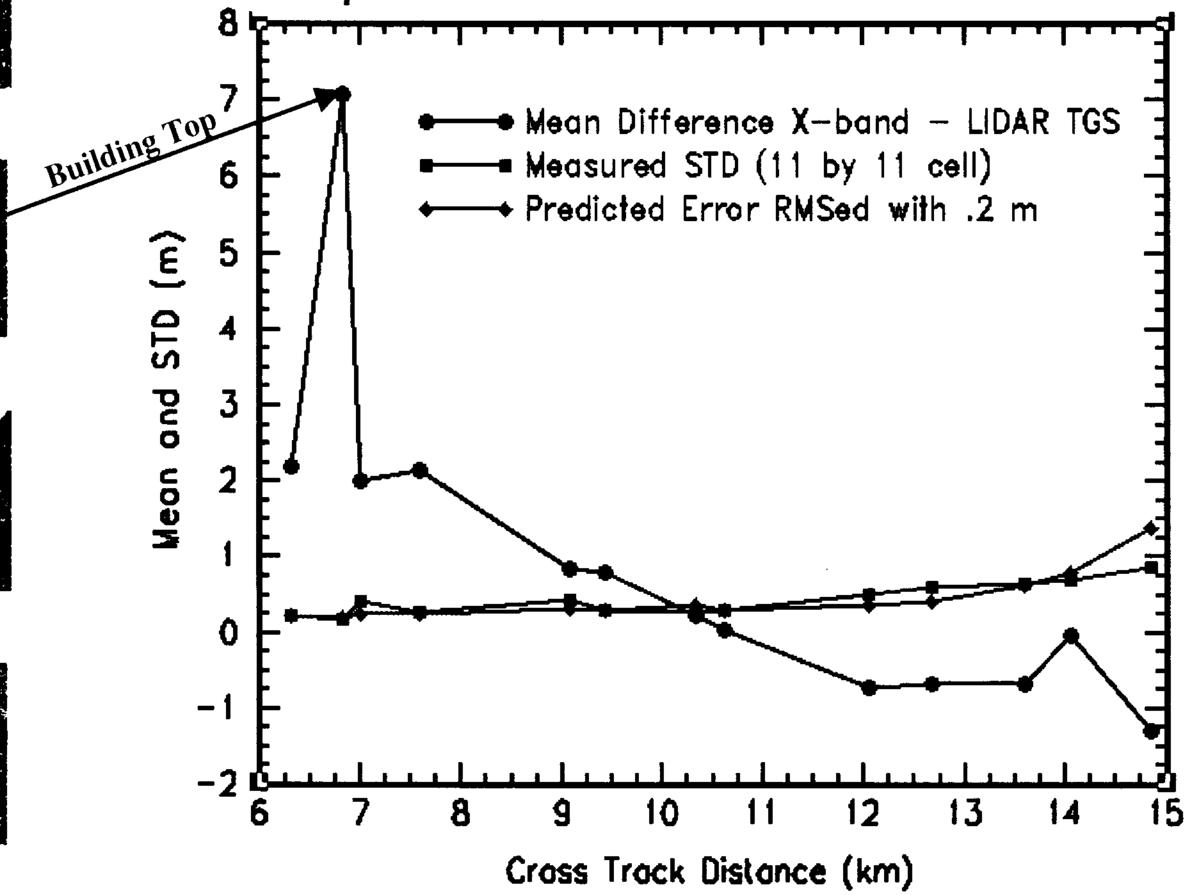

880

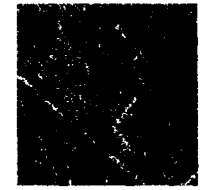

982

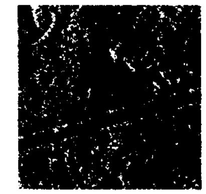

1018

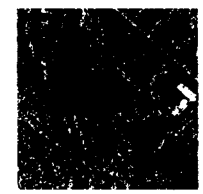

1133

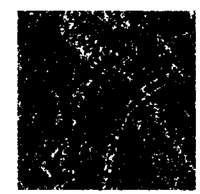
Comparison of EDI LIDAR TGS and X-band in Clear Areas



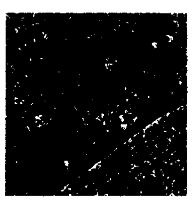

2533

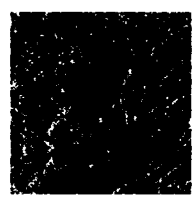

2426

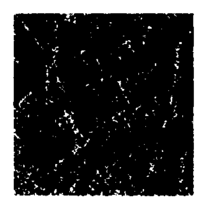

2335

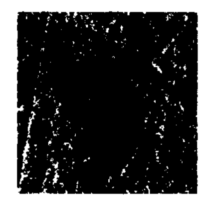

2150


1432


1504


1682

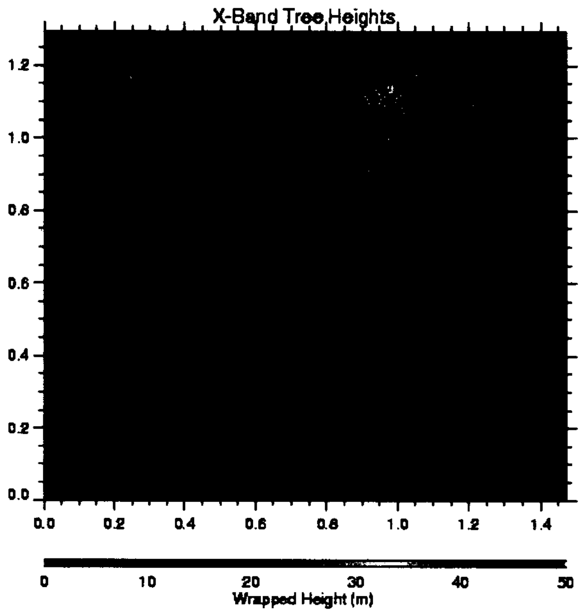

1740

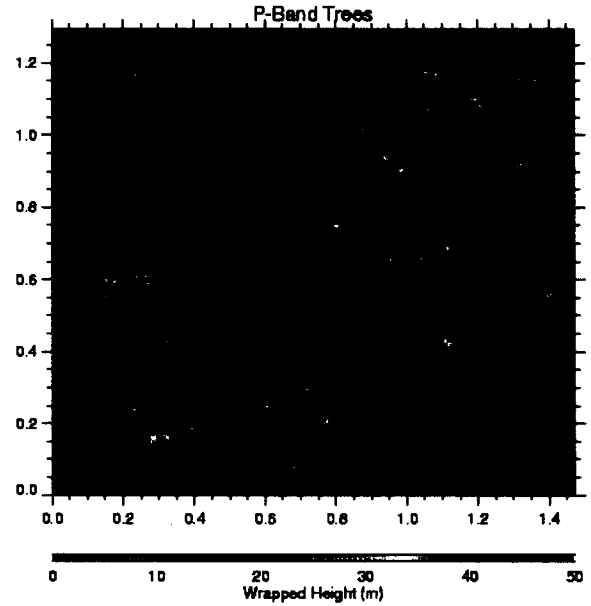

2027

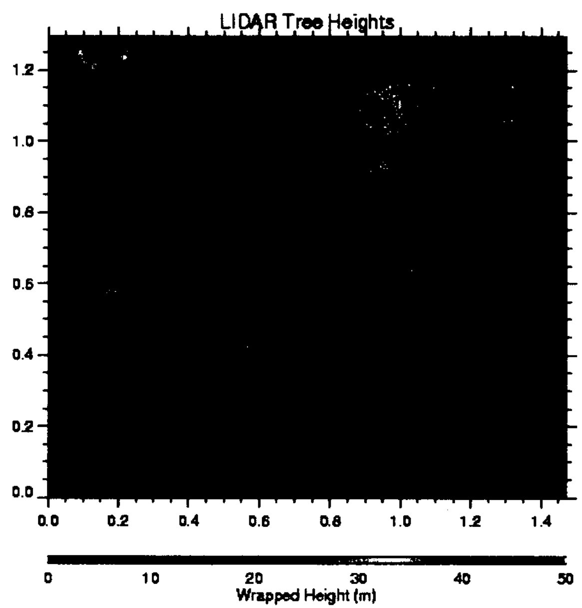
View of Vegetation in Monarch Grove

Photo courtesy of Bruce Allred

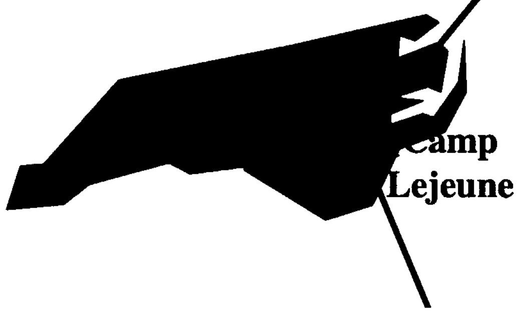
LIDAR, X, and P-band Tree Heights

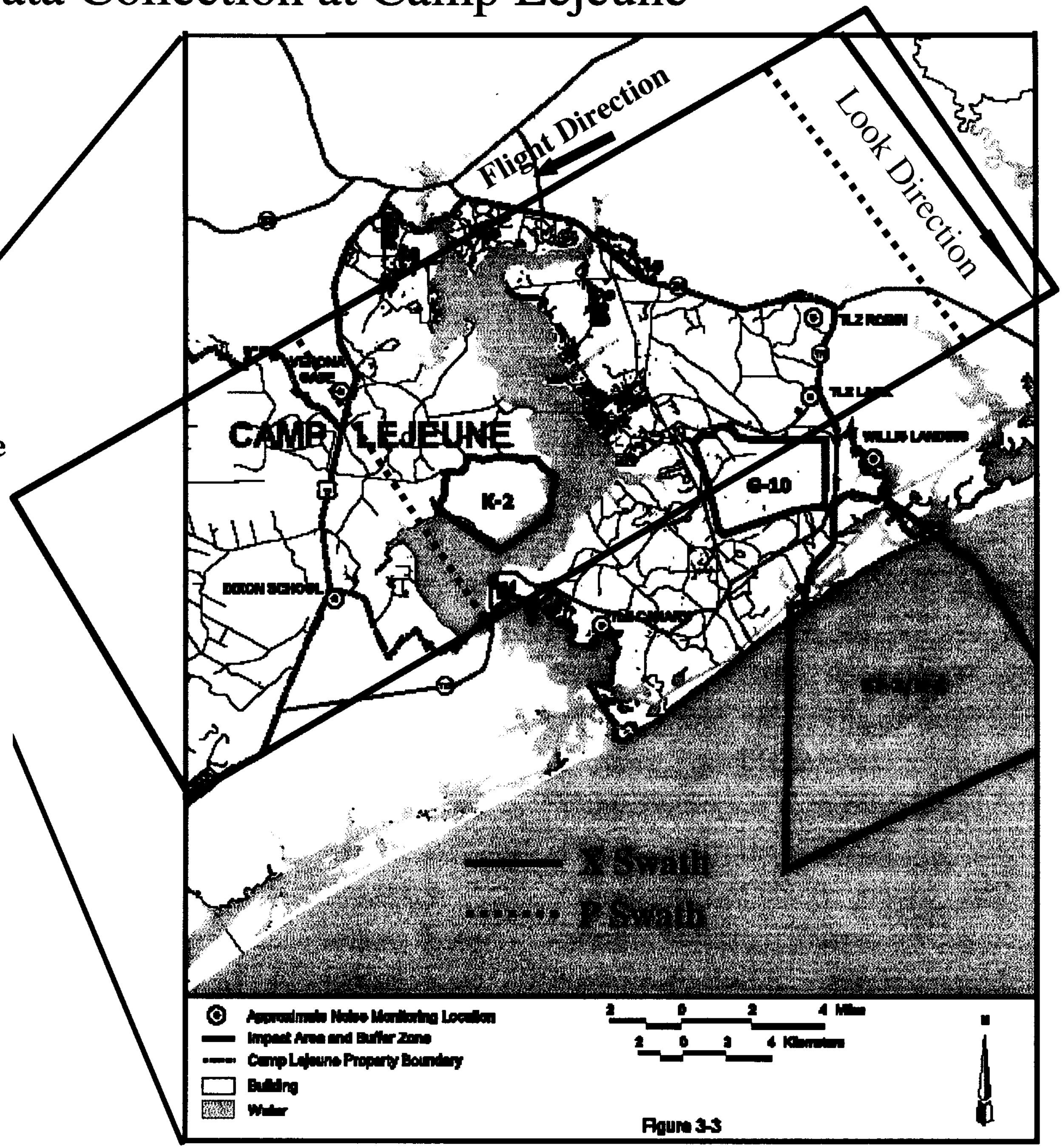






Data Collection at Camp Lejeune





Data Used in Analysis

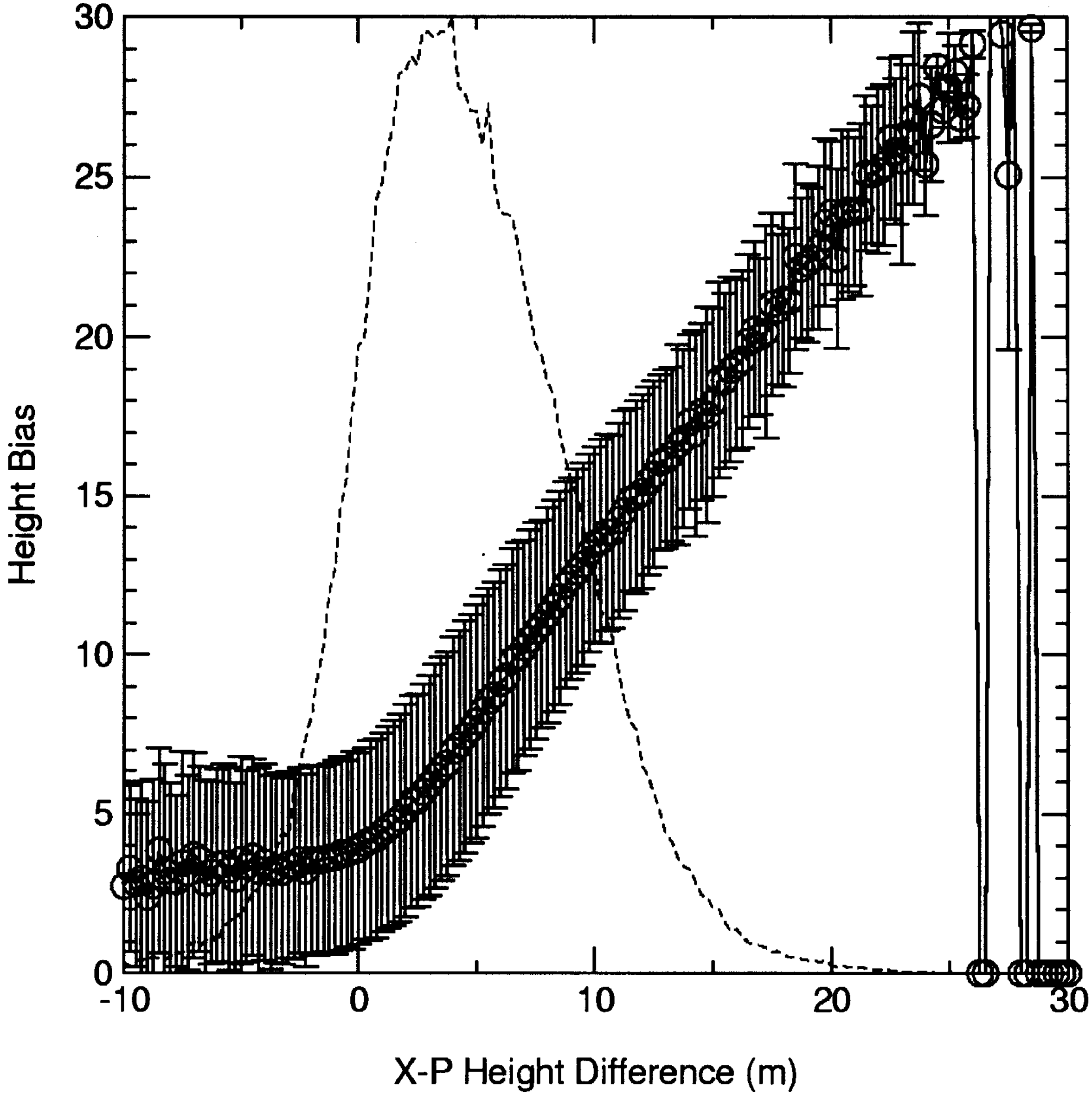
Left Looking
X-band 160 MHz Ping-Pong
P-band 160 MHz Ping-Pong
P-band 160 MHz SAT
Data Posted at 5 m Pixels
Flight Altitude: 8450 m
Heading: -122°
Swath Width: 13 km
Strip Length (X): 45 km
Strip Length (P): 26 km
Date Collected: Oct. 7, 2001

Bruce Allred Photos of Camp Lejeune

• Deciduous vegetation with moderately thick understory.

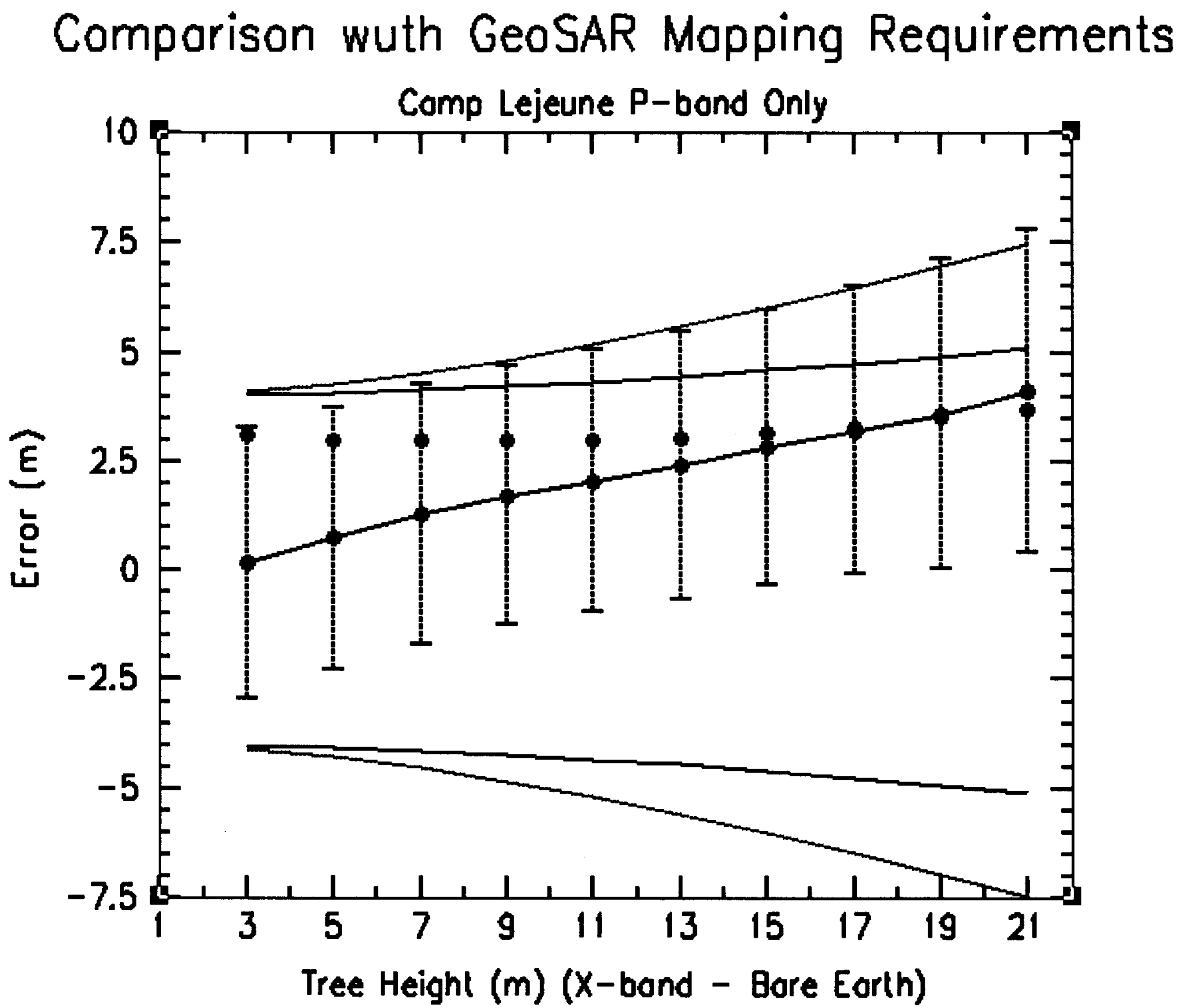
• View along unpaved road showing tree diameters estimated from picture to be between 5 - 50 cm. Estimate tree height between 15-30 m.

Height Bias Correlation to X-P Band Height

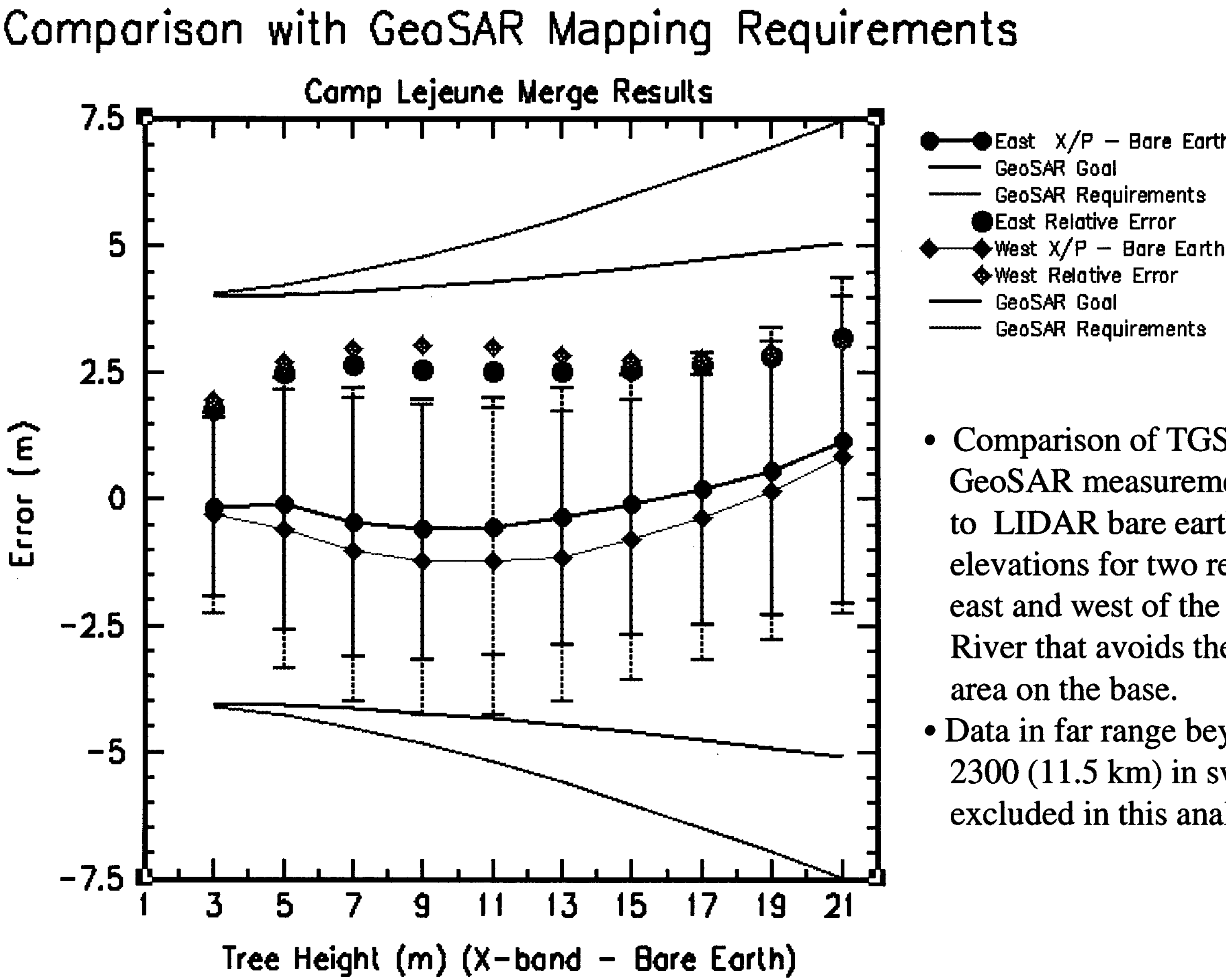


- There is very good agreement between the height bias and the X-P height difference when the X-P difference > 5m
- The mode of the data is below 5m X-P difference, indicating that (given that trees are in the 10m-20m range) the P-band is not measuring the bare surface much of the time.
- A significant fraction of the data shows X-P differences < 0, even when the height bias is > 0.
- Due to these effects, the X-P band heights alone are not sufficient for correcting the height bias.

Comparison with GeoSAR Requirements



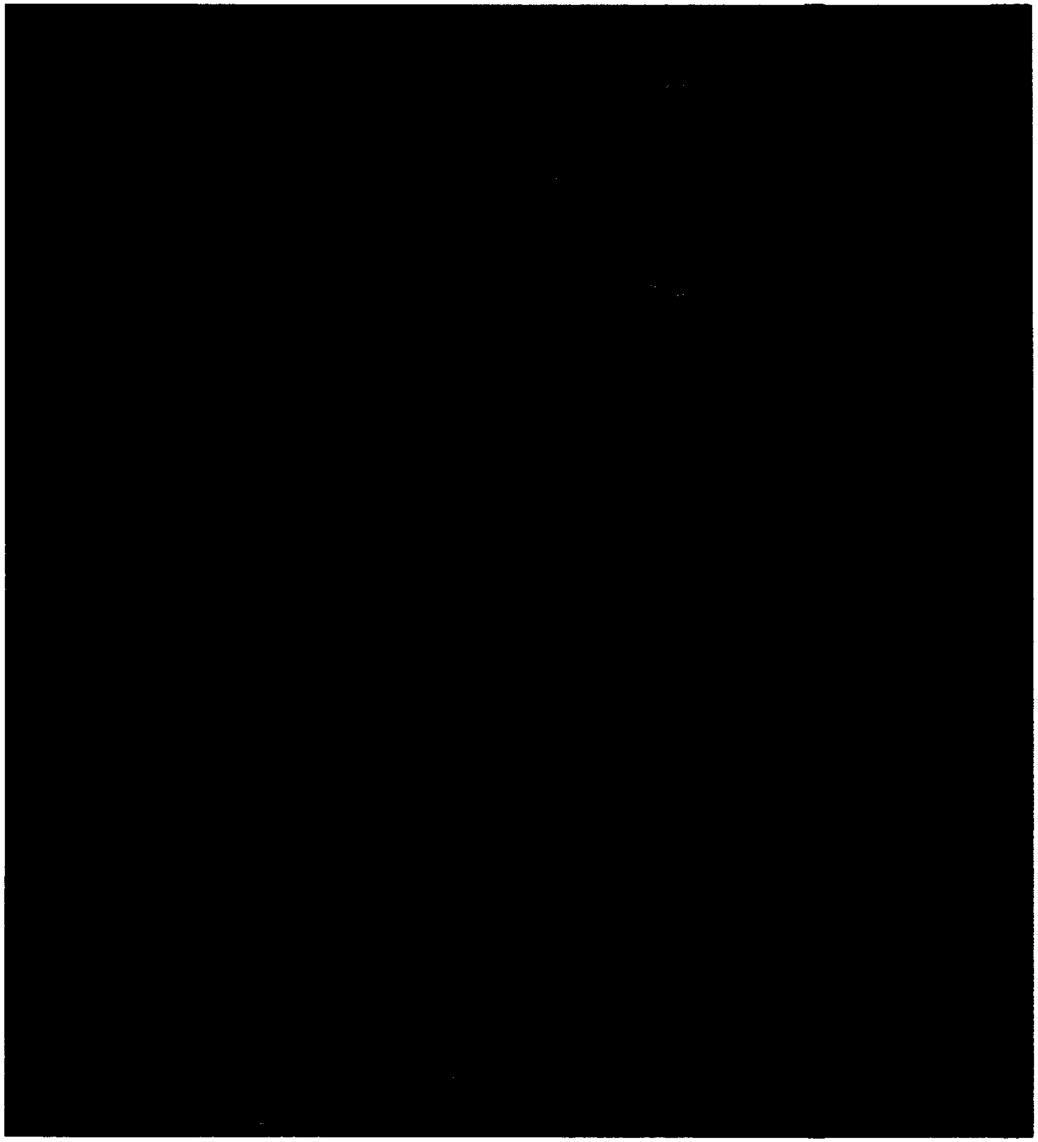
Comparison with Requirements

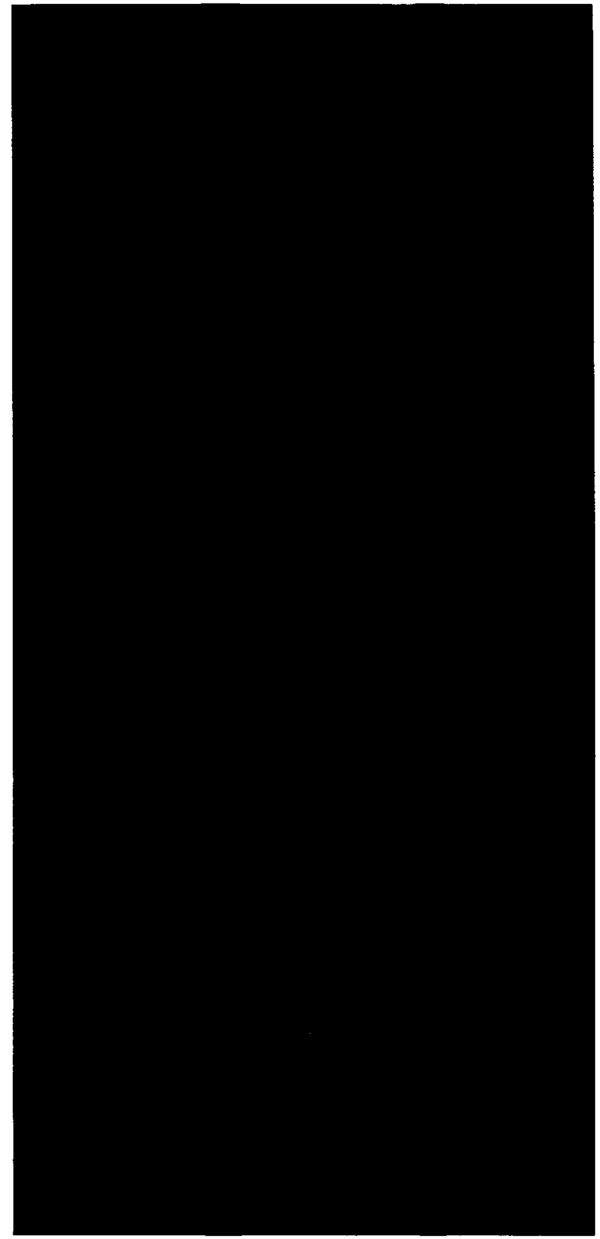


- Comparison of TGS GeoSAR measurements to LIDAR bare earth elevations for two regions east and west of the New River that avoids the urban area on the base.
- Data in far range beyond pixel 2300 (11.5 km) in swath excluded in this analysis.

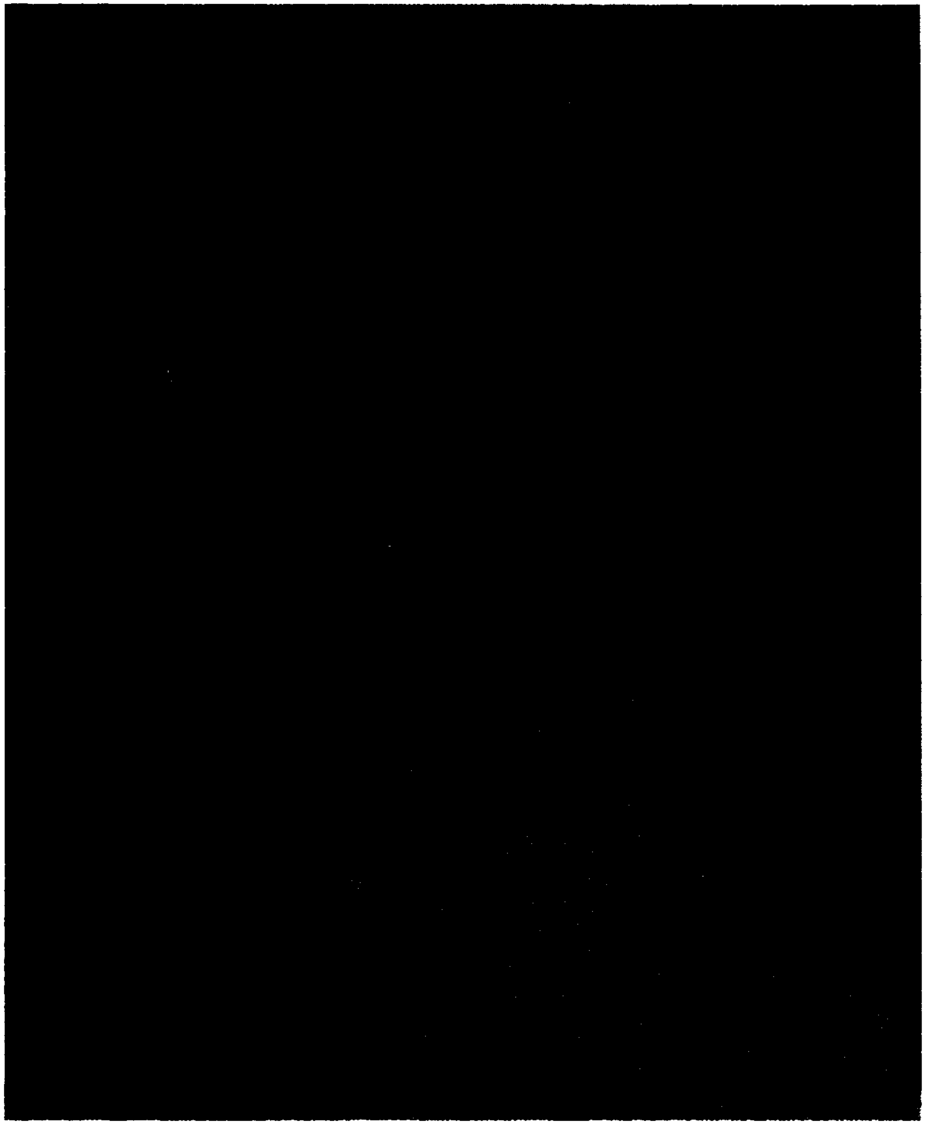
Camp Navajo FOPEN Test Site

X/P Elevation Mosaics at Camp Navajo

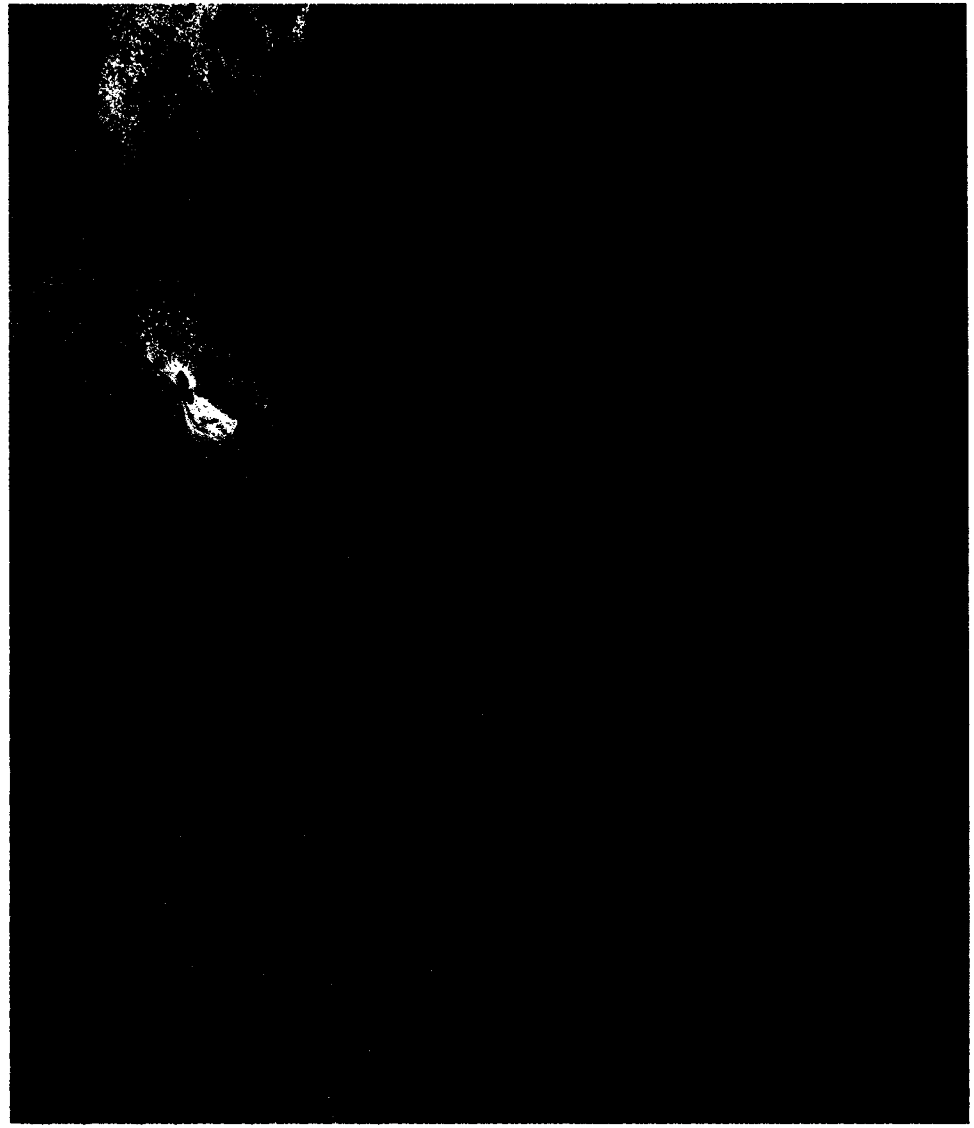




Elevation and Image Combined



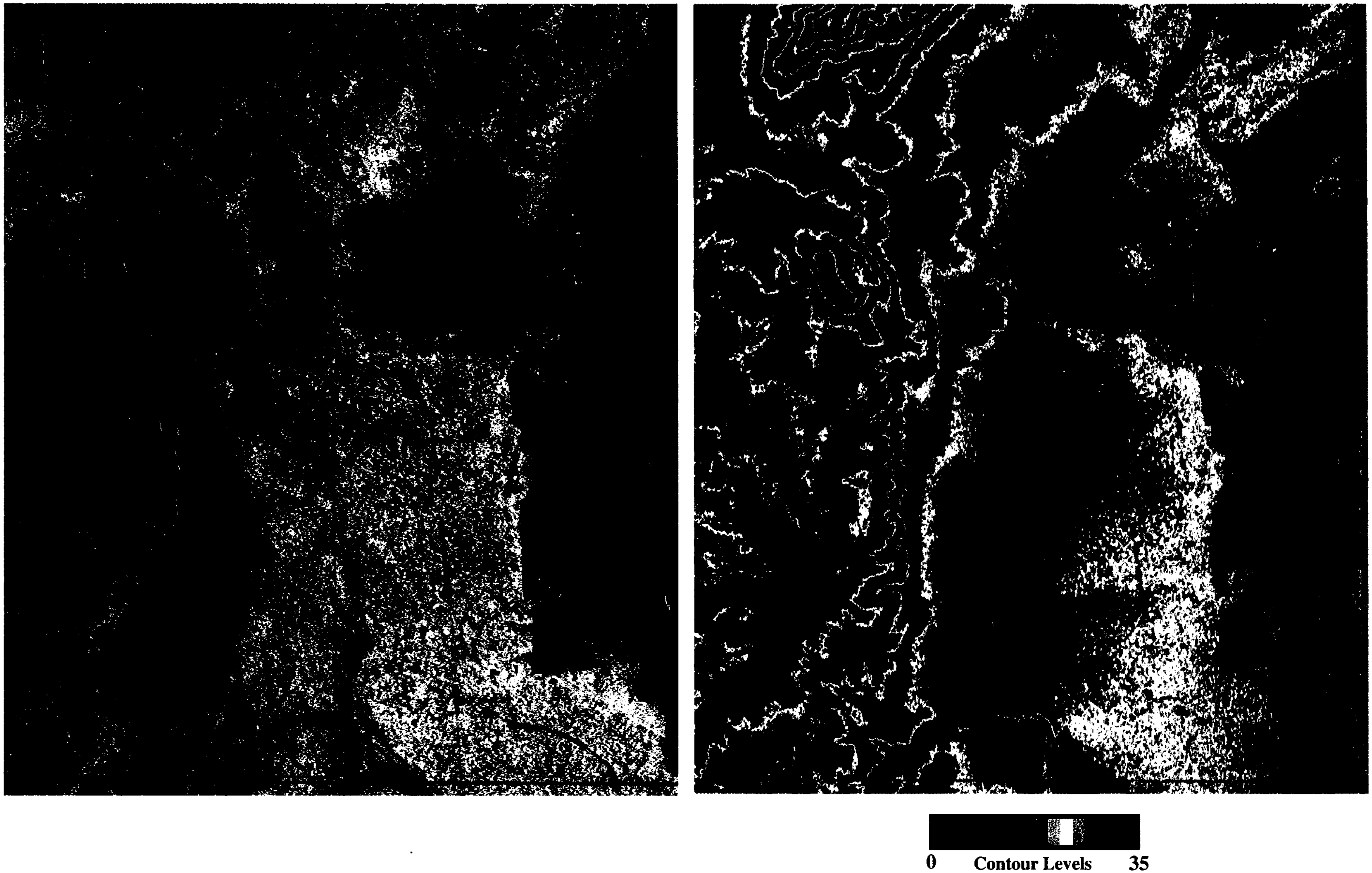
P-Band Image Detail



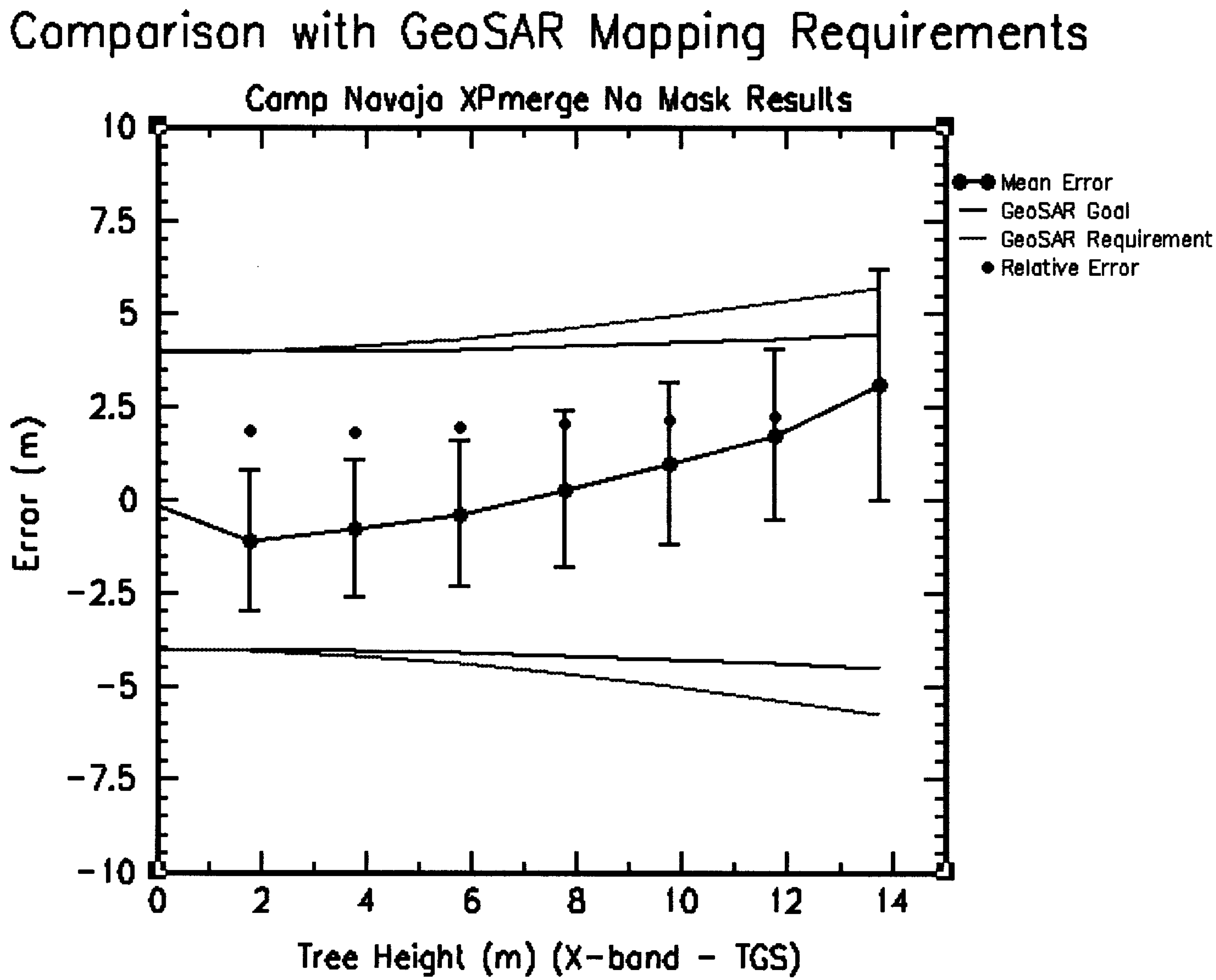
X-Band Image Detail

360 M Color Wrap

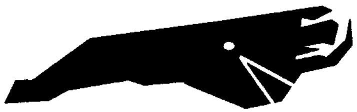
P-band Elevation Data



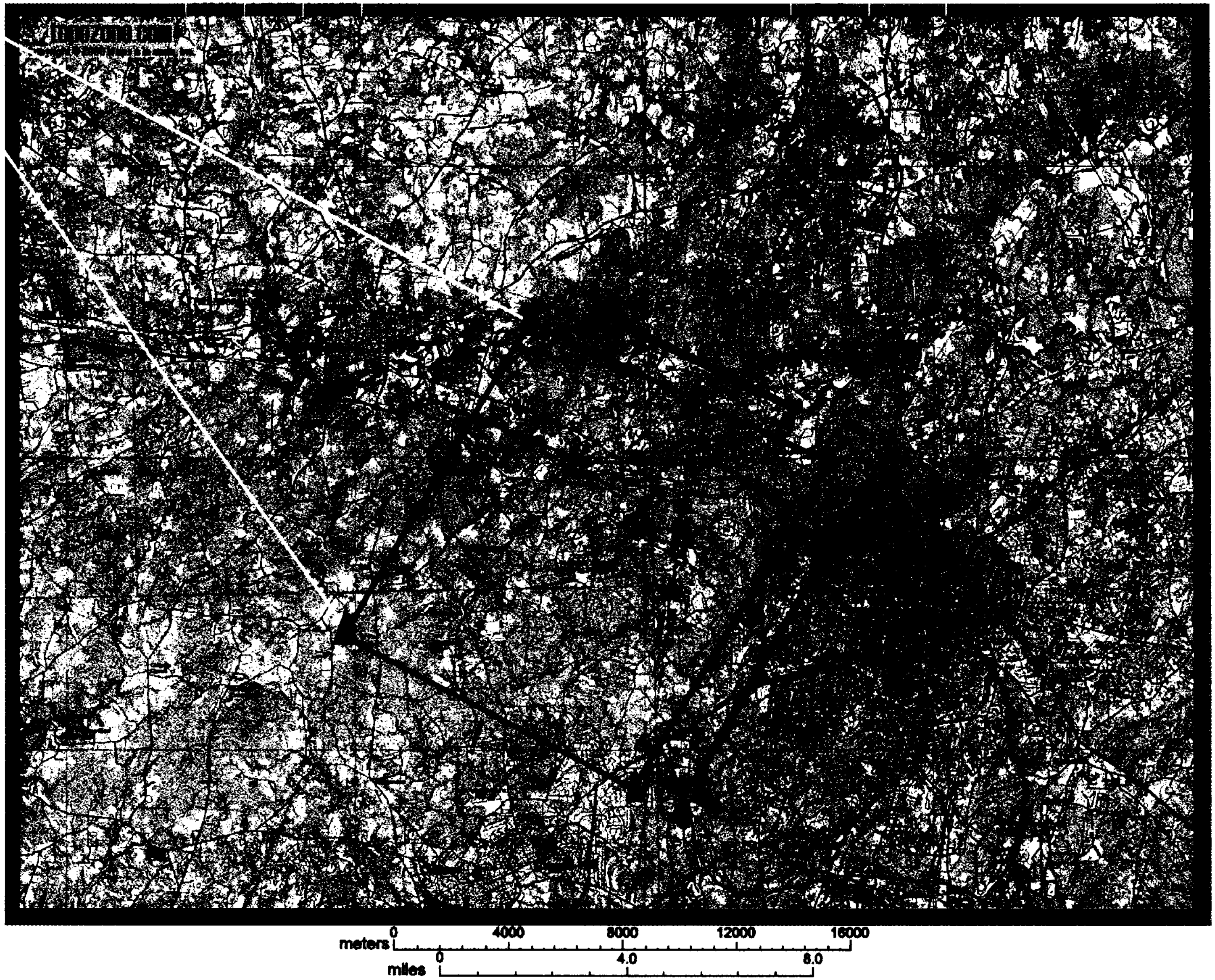
Comparison with GeoSAR Requirements



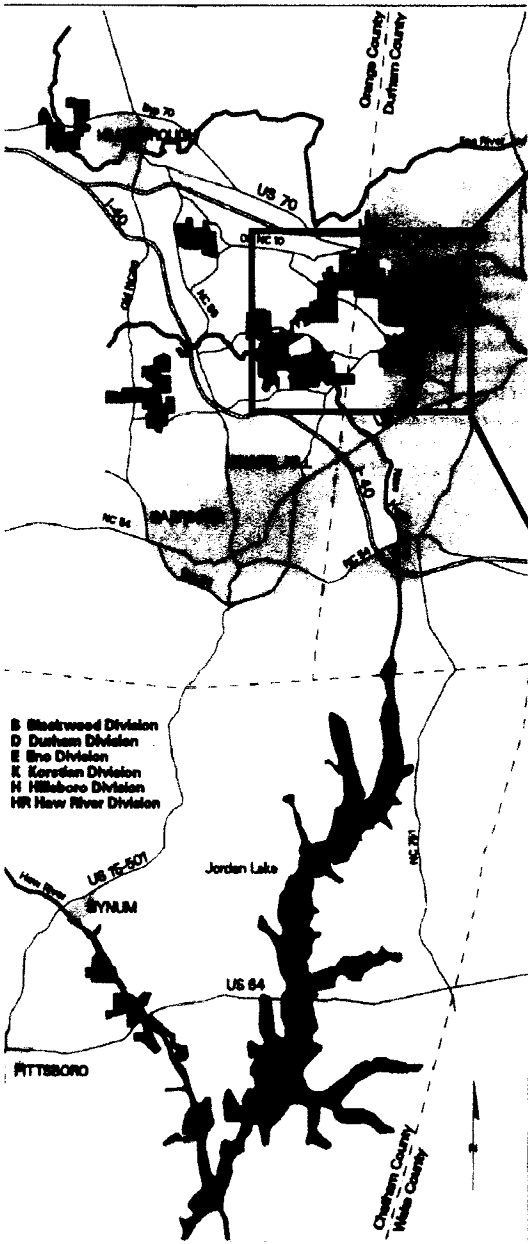
Duke Data Collection



- **Collected 15 lines at Duke Forests on October 11, 2001.**
- **Processed data from Flight 2 ADT 1 for data analysis.**
- **Imaging Details:**
  Altitude: 8915 m
  Heading: 39°
  Bandwidth: 160
  Image Direction: Left
  Modes: XLP, ULS, ULC
  Swath Width: 13 km
  Strip Length: 15 km
  Mean Terrain Hgt: 130 m

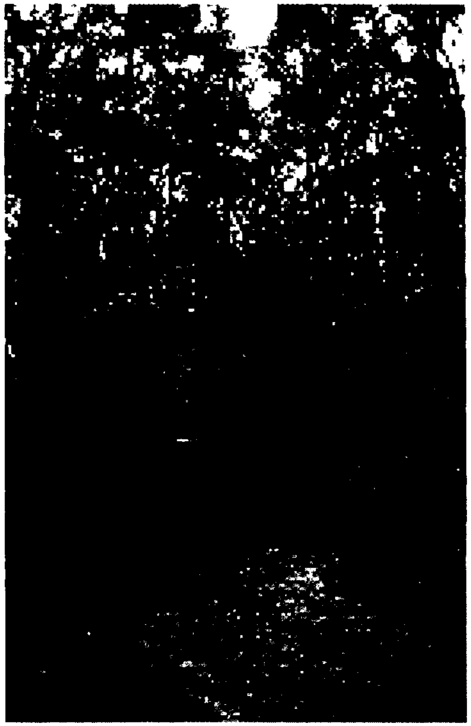


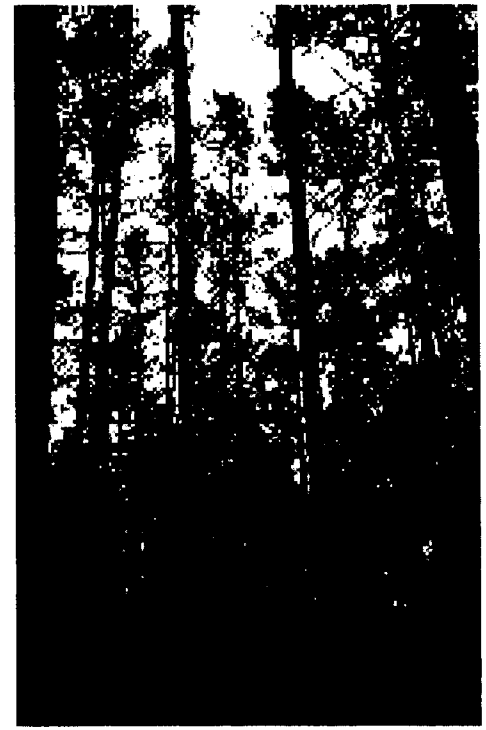
Duke Forest Experimental Plots

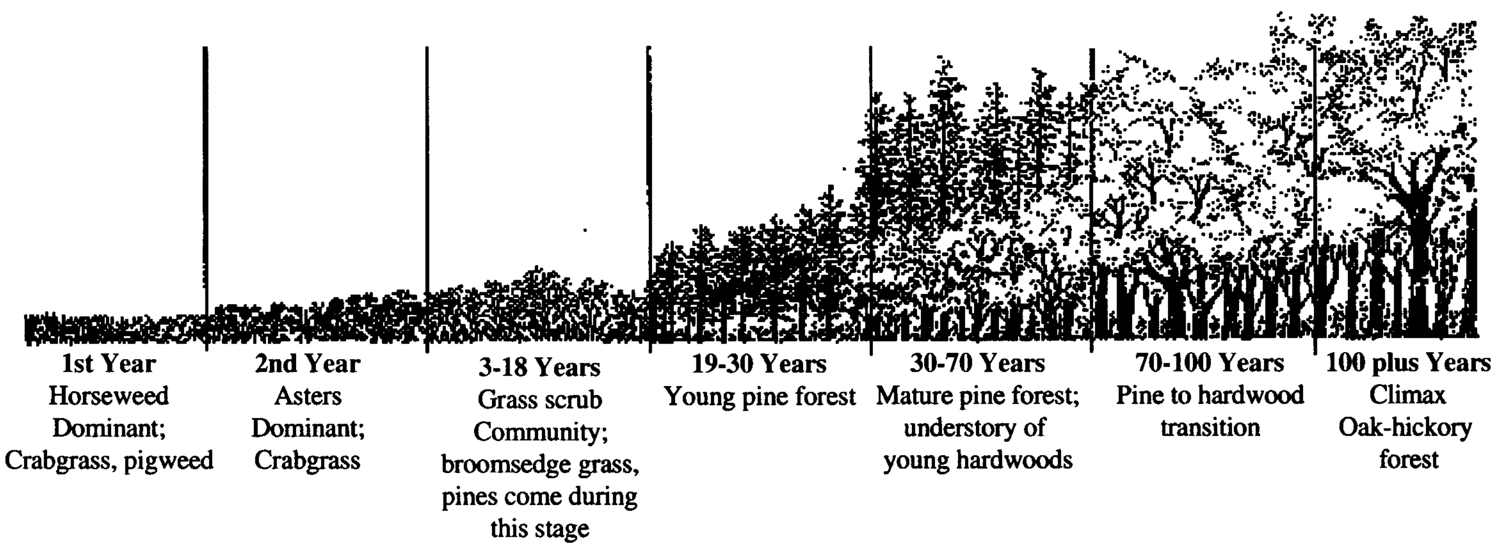


- Duke Forest areas are highlighted in dark green. Forested areas within the red box were imaged by GeoSAR.

Duke Vegetation

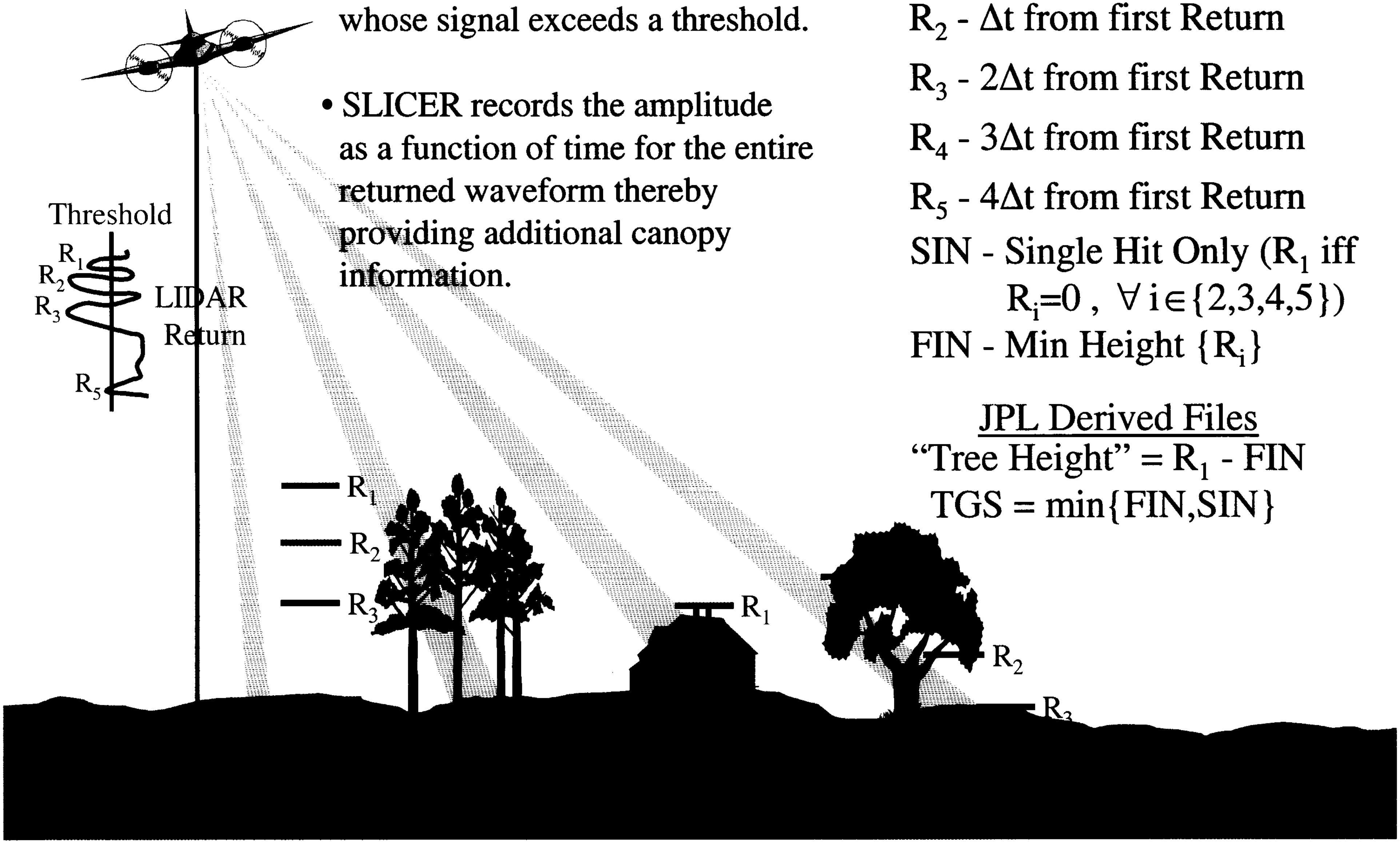






LIDAR Data

- Earthdata LIDAR records height of at most 5 returns whose signal exceeds a threshold.
- SLICER records the amplitude as a function of time for the entire returned waveform thereby providing additional canopy information.



<u>Earthdata LIDAR Files</u>

R_1 - First Return

R_2 - Δt from first Return

R_3 - $2\Delta t$ from first Return

R_4 - $3\Delta t$ from first Return

R_5 - $4\Delta t$ from first Return

SIN - Single Hit Only (R_1 iff $R_i = 0, \ \forall i \in \{2,3,4,5\}$)

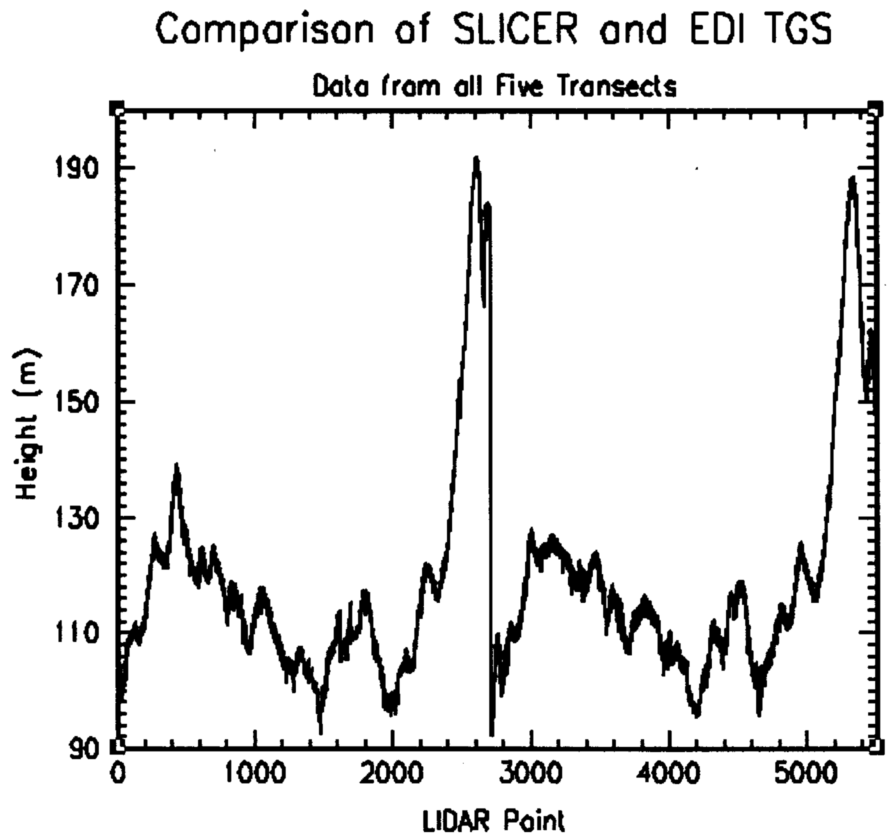
FIN - Min Height $\{R_i\}$

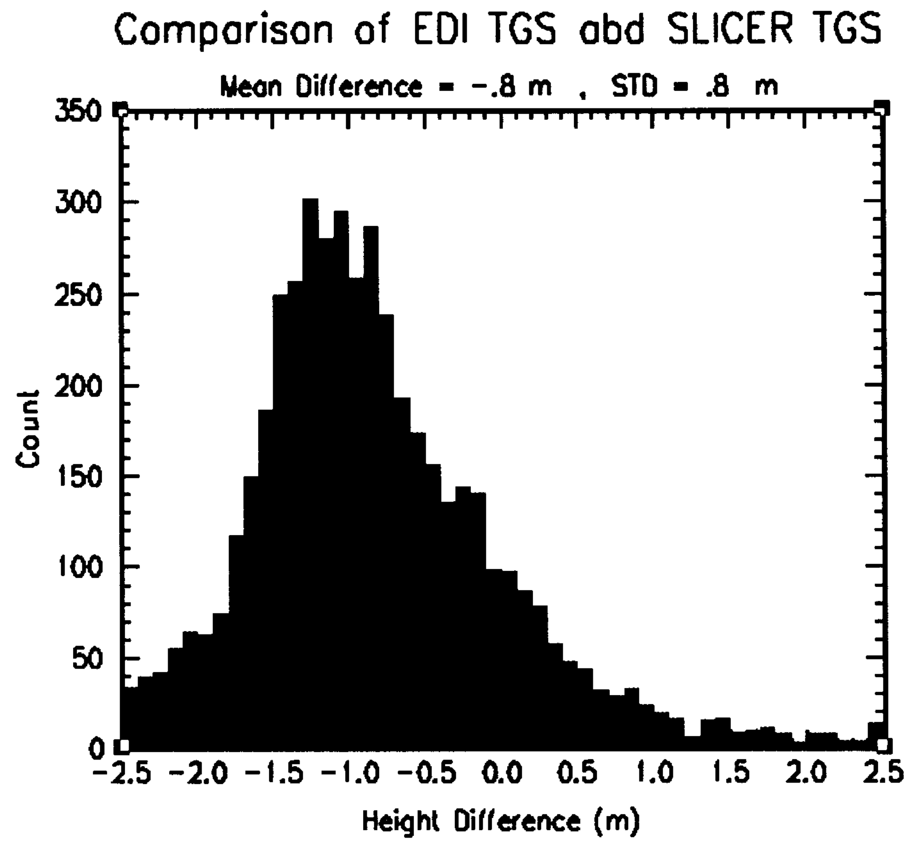
<u>JPL Derived Files</u>

"Tree Height" = R_1 - FIN

TGS = $\min\{\text{FIN},\text{SIN}\}$

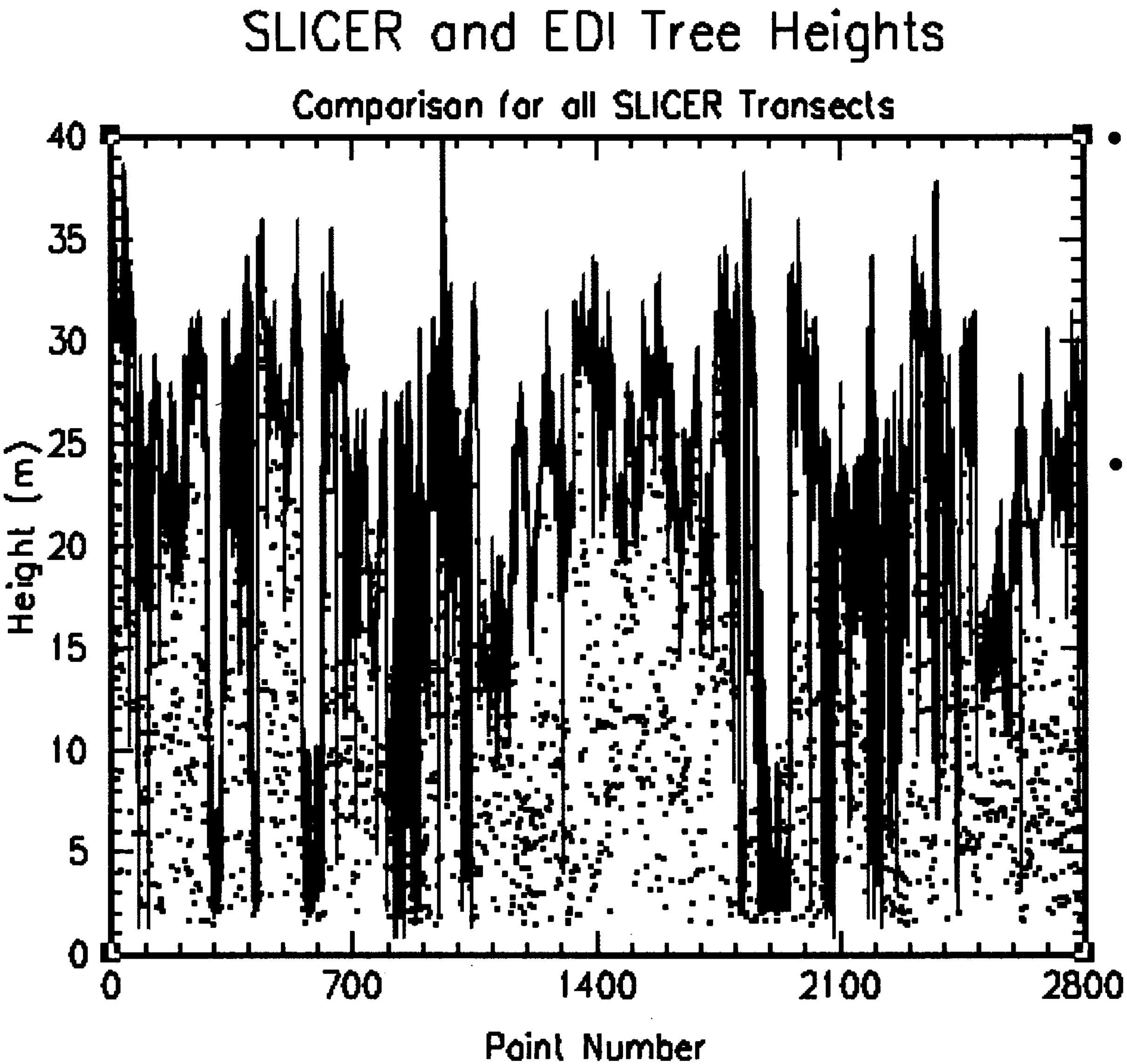
SLICER TGS and EDI TGS Comparison





- EDI TGS and SLICER TGS are in very good agreement. Mean bias of .8 m is probably JPL removal of the geoid using EGM96 does not match the one applied to the data. Since the SLICER data was not filtered except for obvious outliers the .8 m standard deviation seems reasonable.

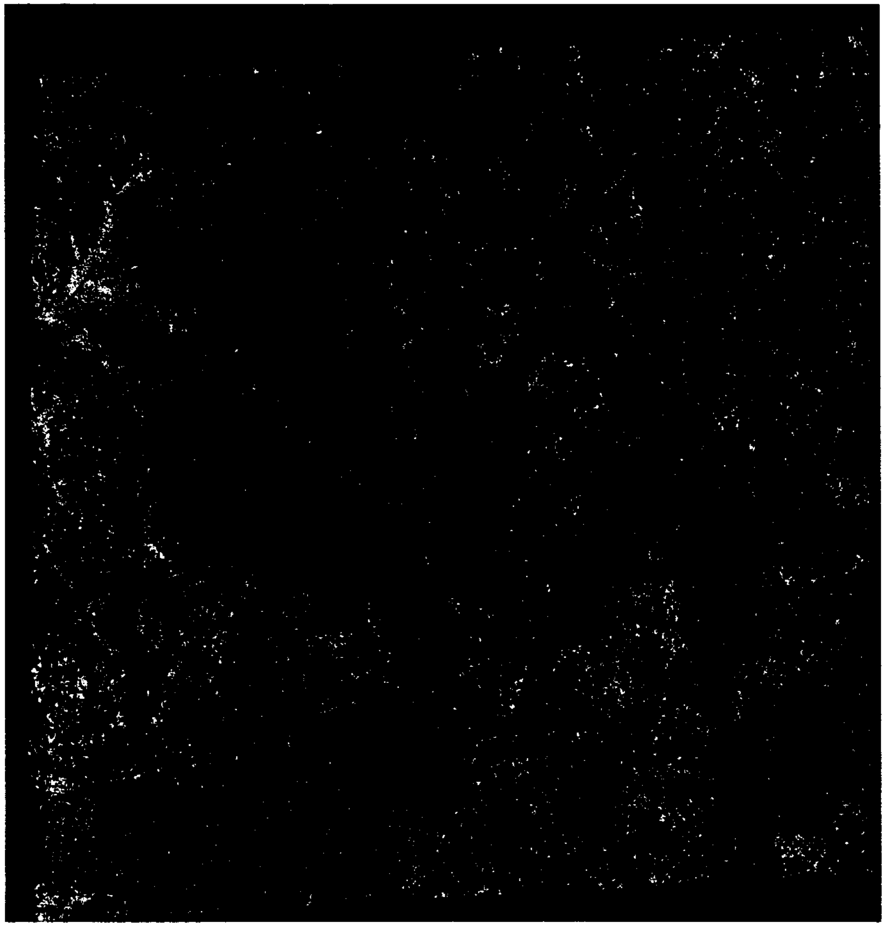
SLICER and EDI LIDAR Tree Height

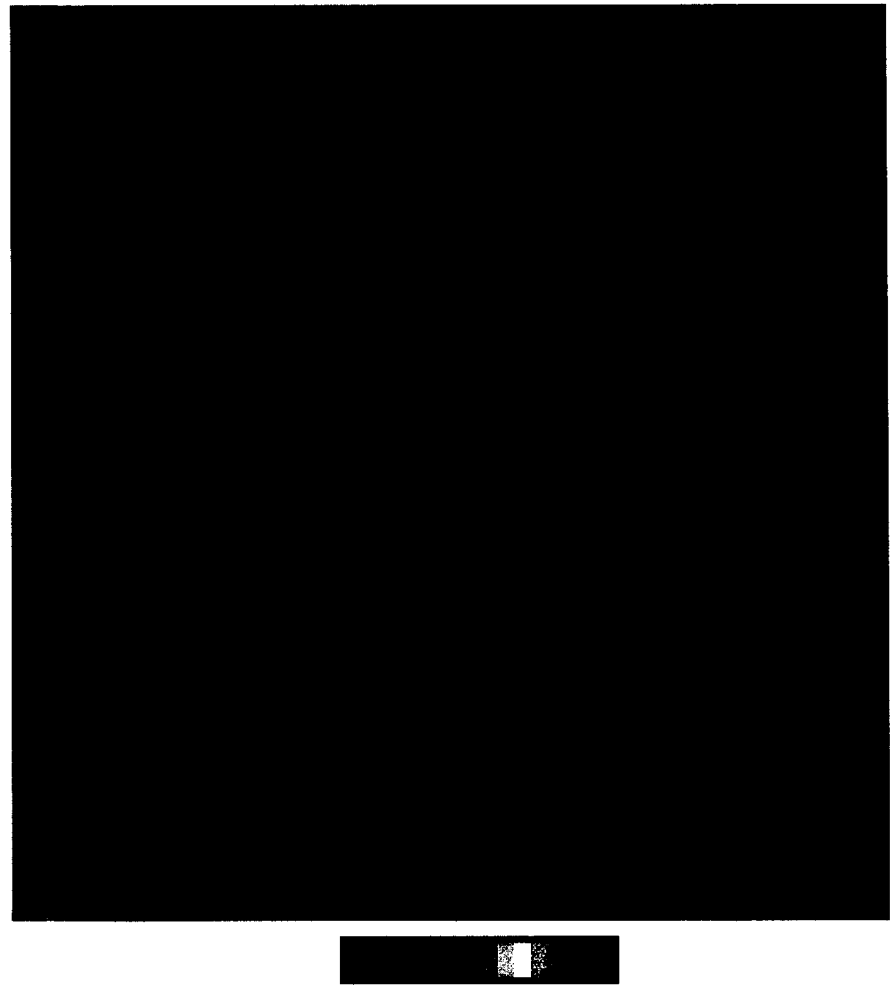


- EDI tree heights often peak at or near the same tree heights as the SLICER data but the spread of values throughout the canopy is considerably larger.
- Difference may be a result of collecting data in leaf-off conditions.

Mean EDI TH:	**11.9 m**
STD EDI TH:	**8.2 m**
Mean SLICER TH:	**21.8 m**
STD SLICER TH:	**7.3 m**
Mean Difference:	**-10.0 m**
STD Difference:	**8.6 m**

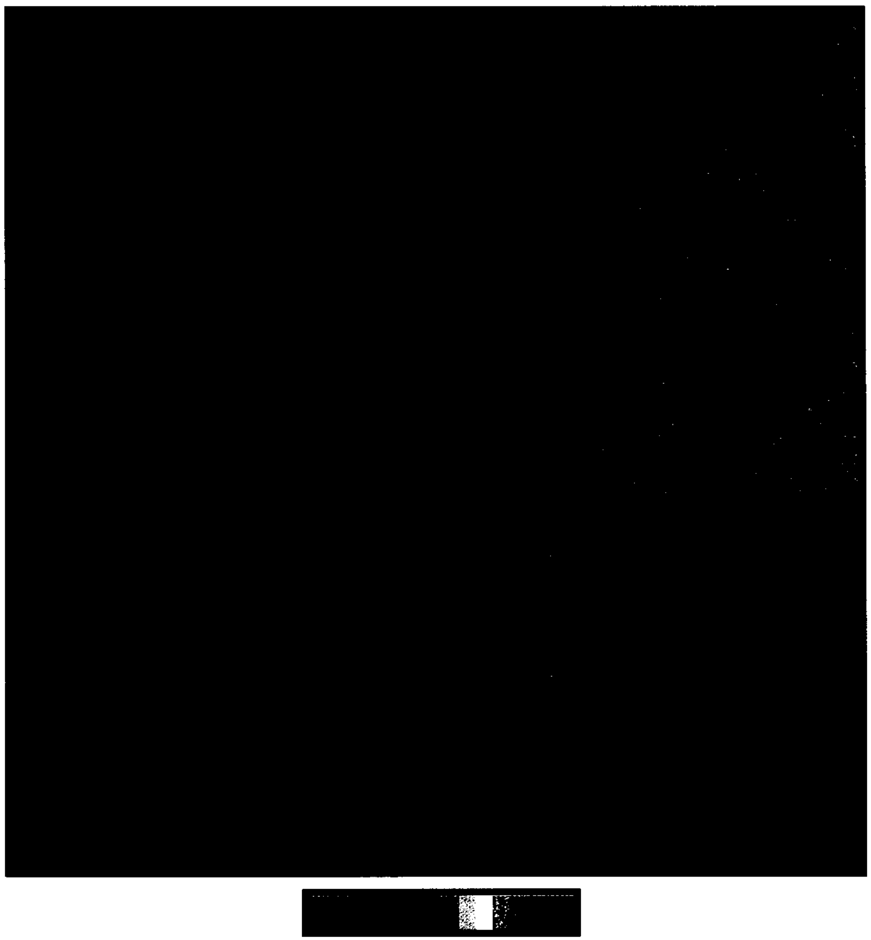
P-band Data



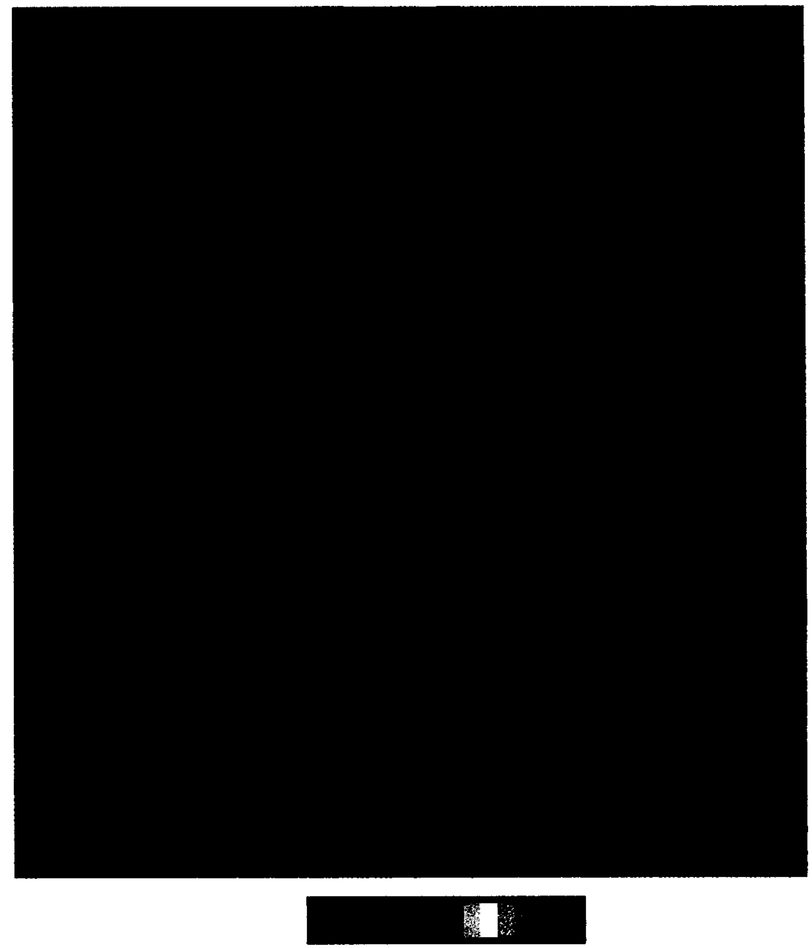


P-band Compared to X-band and LIDAR TGS

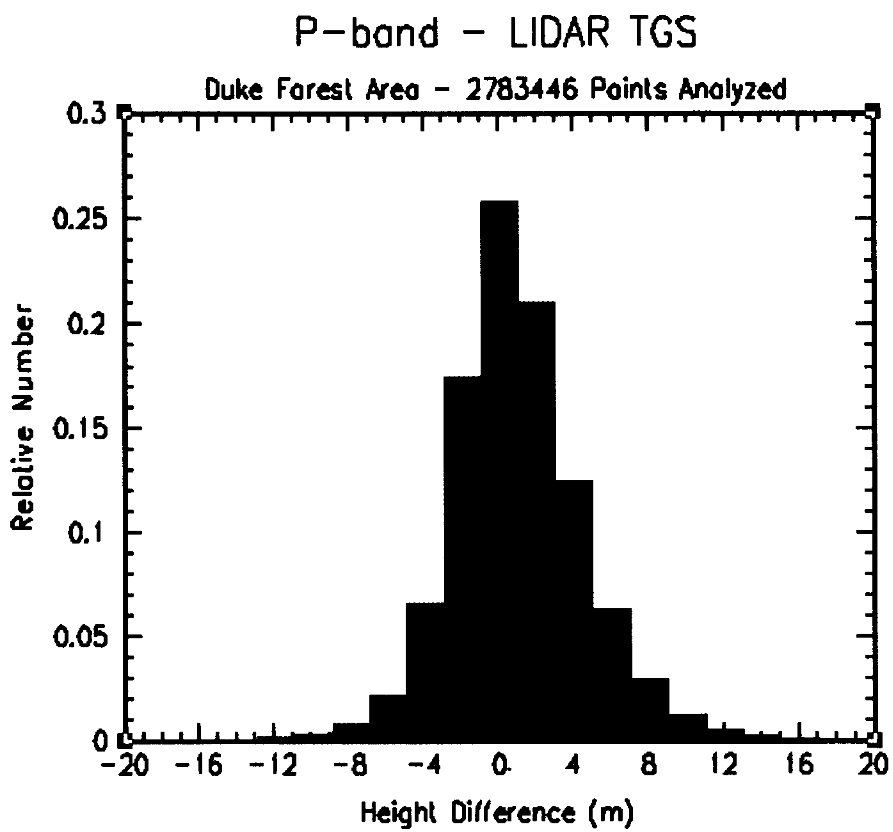
P-band - LIDAR TGS



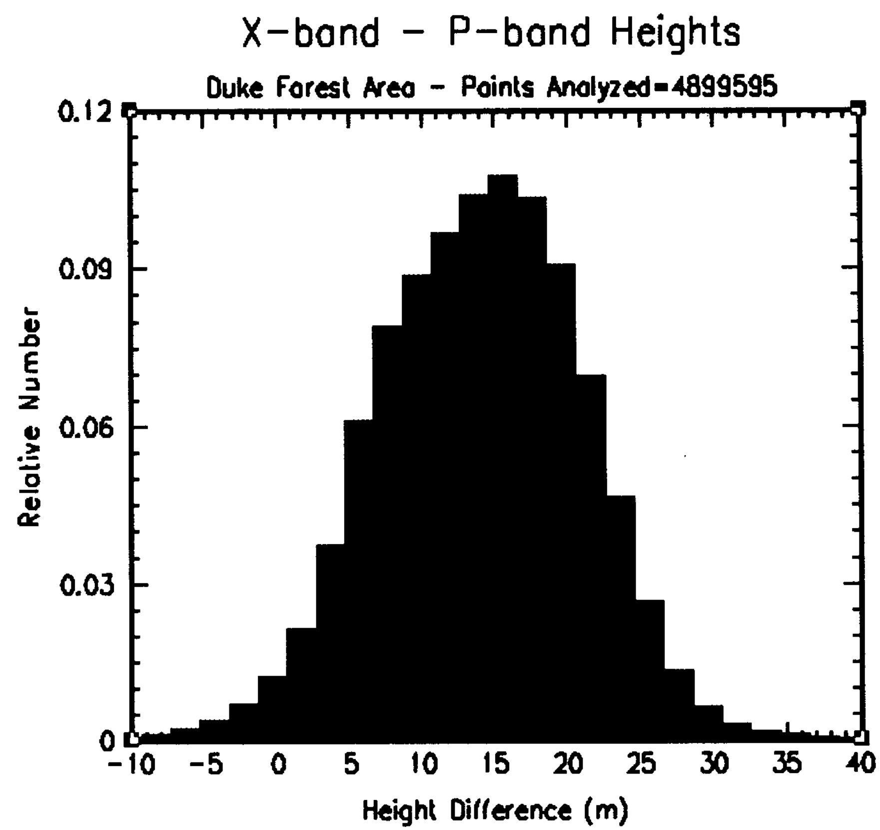
P-band - X-band



Quantitative Assessment of Differences



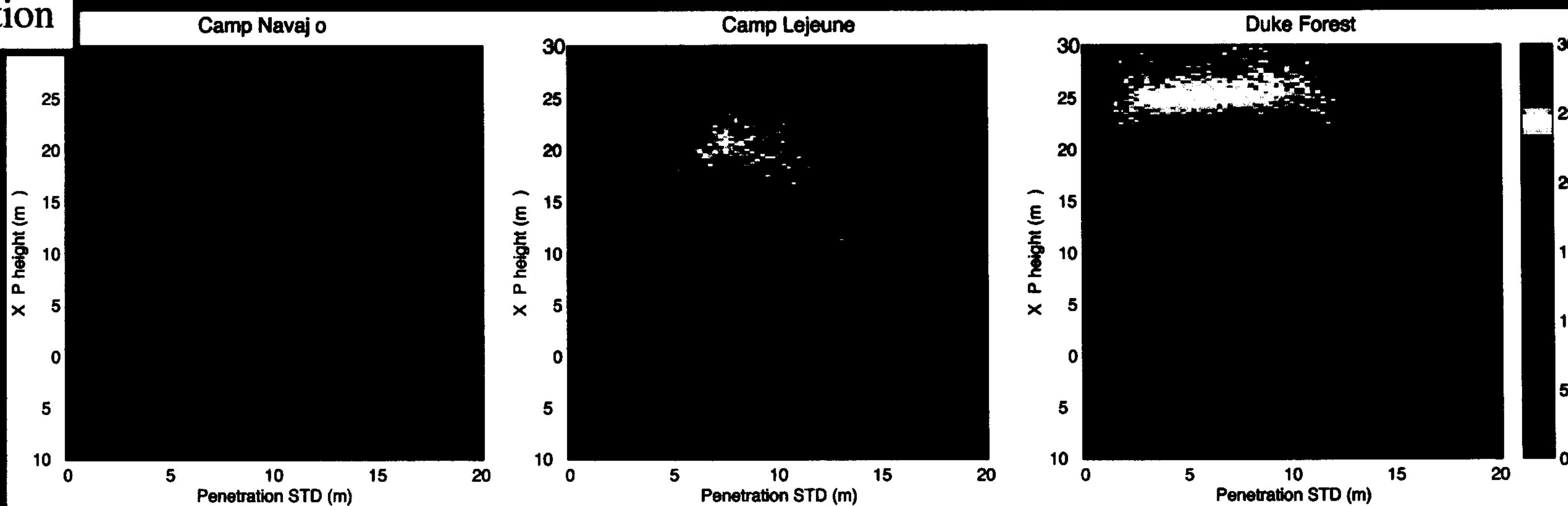
Mean*: .1 m
Std: 4.4 m



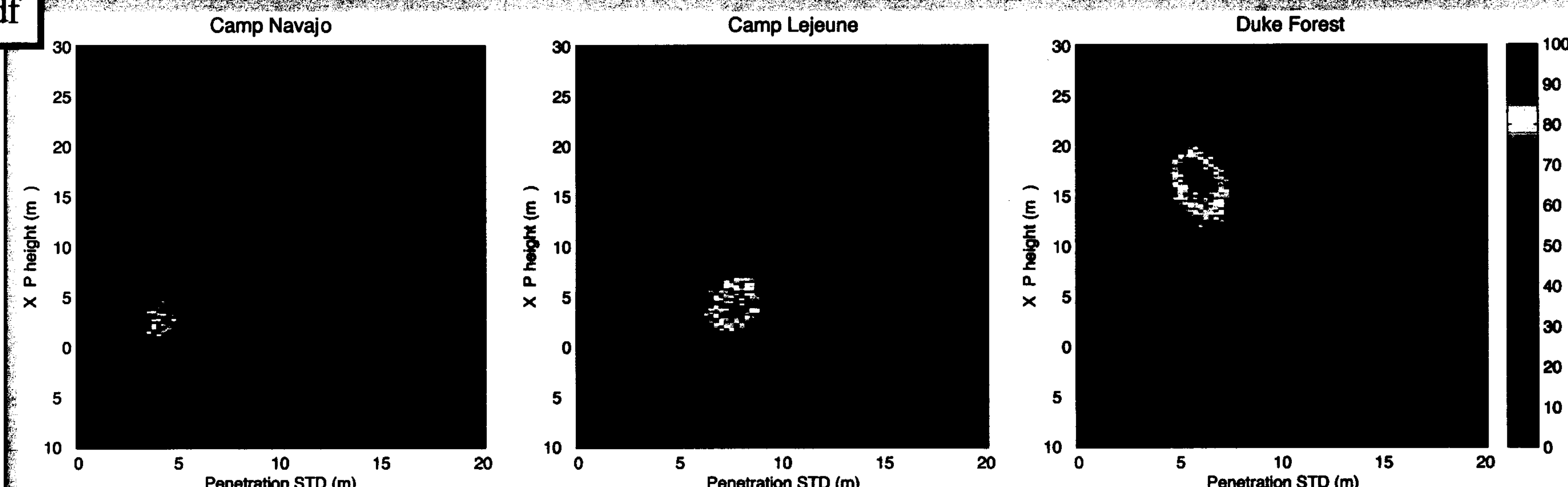
Mean: 12.9 m
Std: 7.7 m

Comparison between study regions

penetration

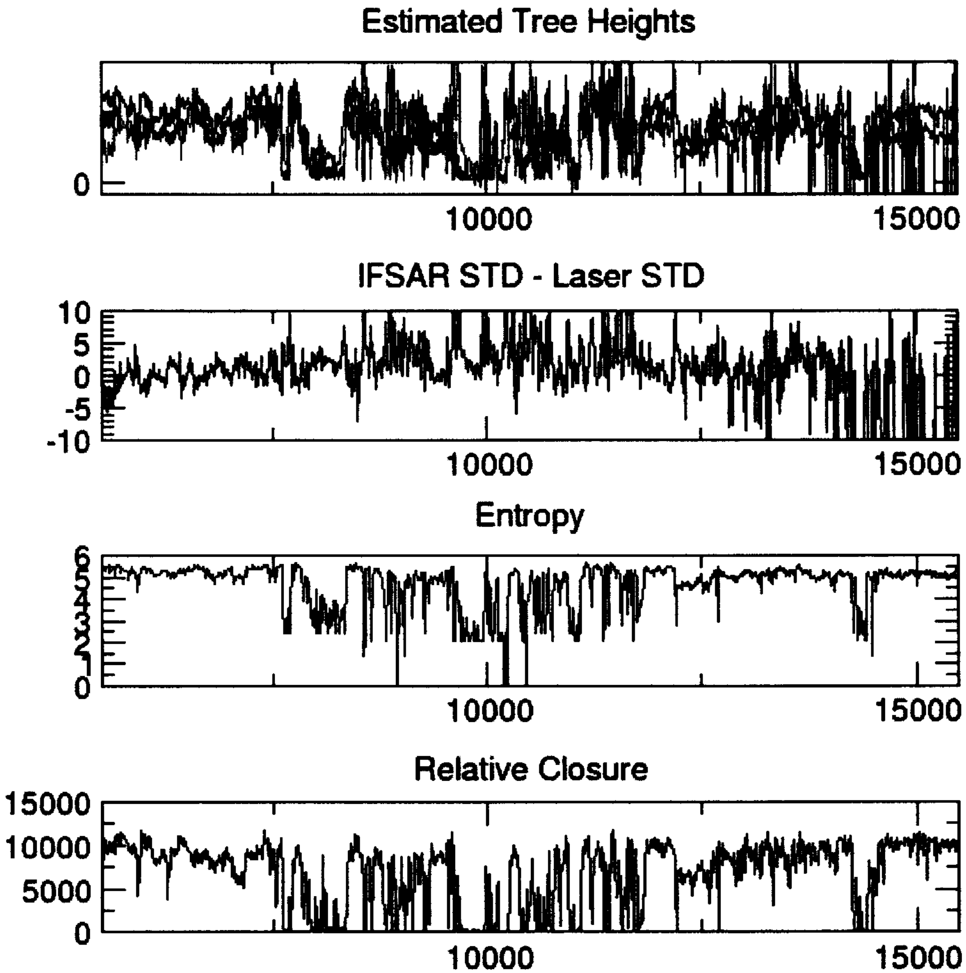


pdf



Example SLICER Transect and Canopy Parameters

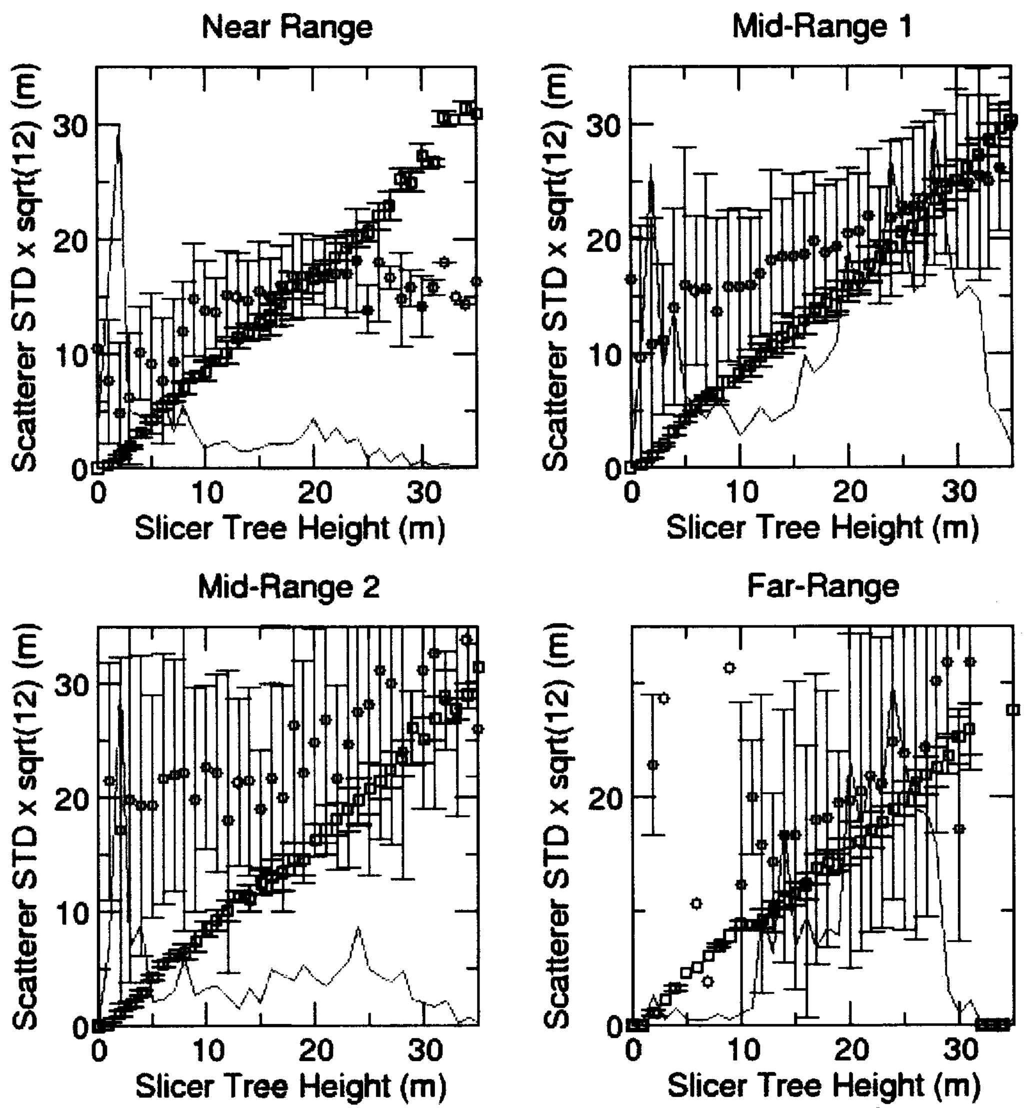
94100507.dat_simpleest_xbnd_1.dat.adat



Entropy measures canopy inhomogeneity

Closure measure amount of radiation reaching the ground

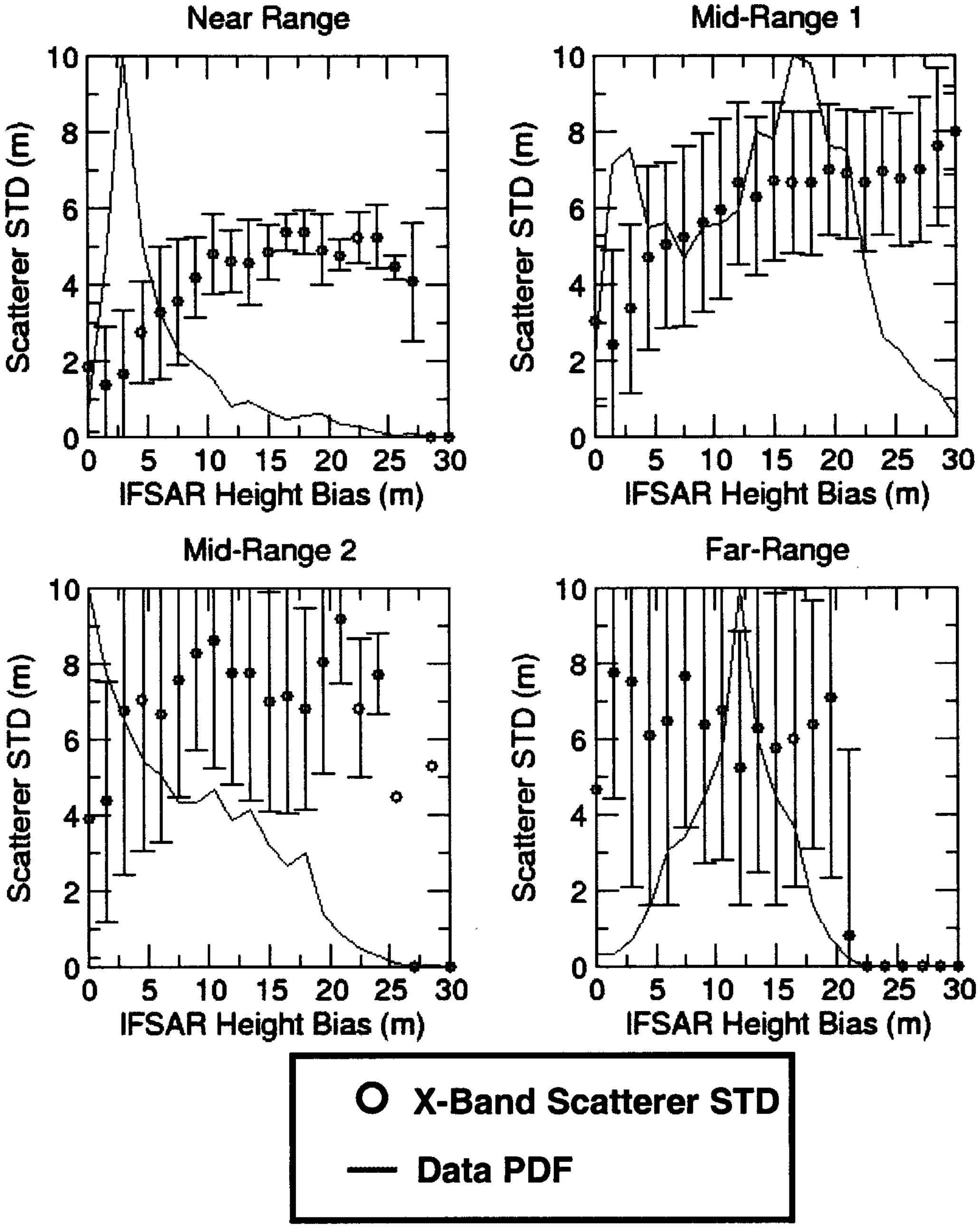
X-Band Scatterer STD vs Tree Height



- Laser Scatterer STD
- X-Band Scatterer STD
- Data PDF

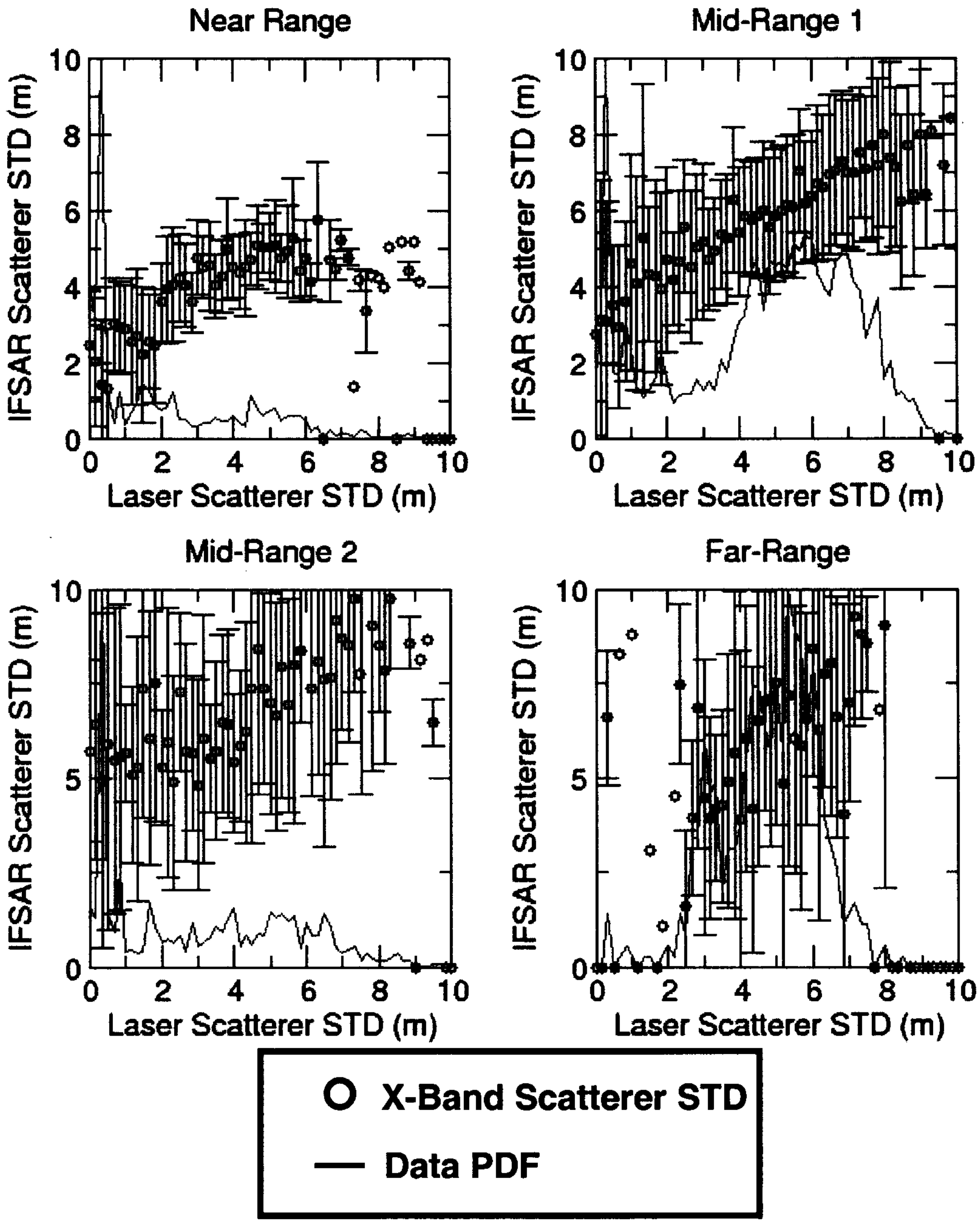
- The tree height is estimated from the laser first/last return height difference
- The laser scatterer STD is almost perfectly correlated with the tree height
- The X-Band scaterer STD also shows a correlation with tree height
- The degree of correlation degrades with cross-track distance (or incidence angle)
- The source for this degradation may be physical (angular dependence of penetration) or a residual calibration effect.
- The correlation deviates most at small values of tree height.

X-Band Scatterer STD vs Height Bias



- **The height bias is estimated by taking the difference between the X-Band heights and the Laser last return.**
- **The dependence of the height bias is similar to that of tree height, but the correlation is somewhat lower:**
    - This is expected since the scatterer STD measures the dispersion of scatterers as a function of height, which should be proportional to the tree height.

X-Band Scatterer STD vs Laser Scatterer STD

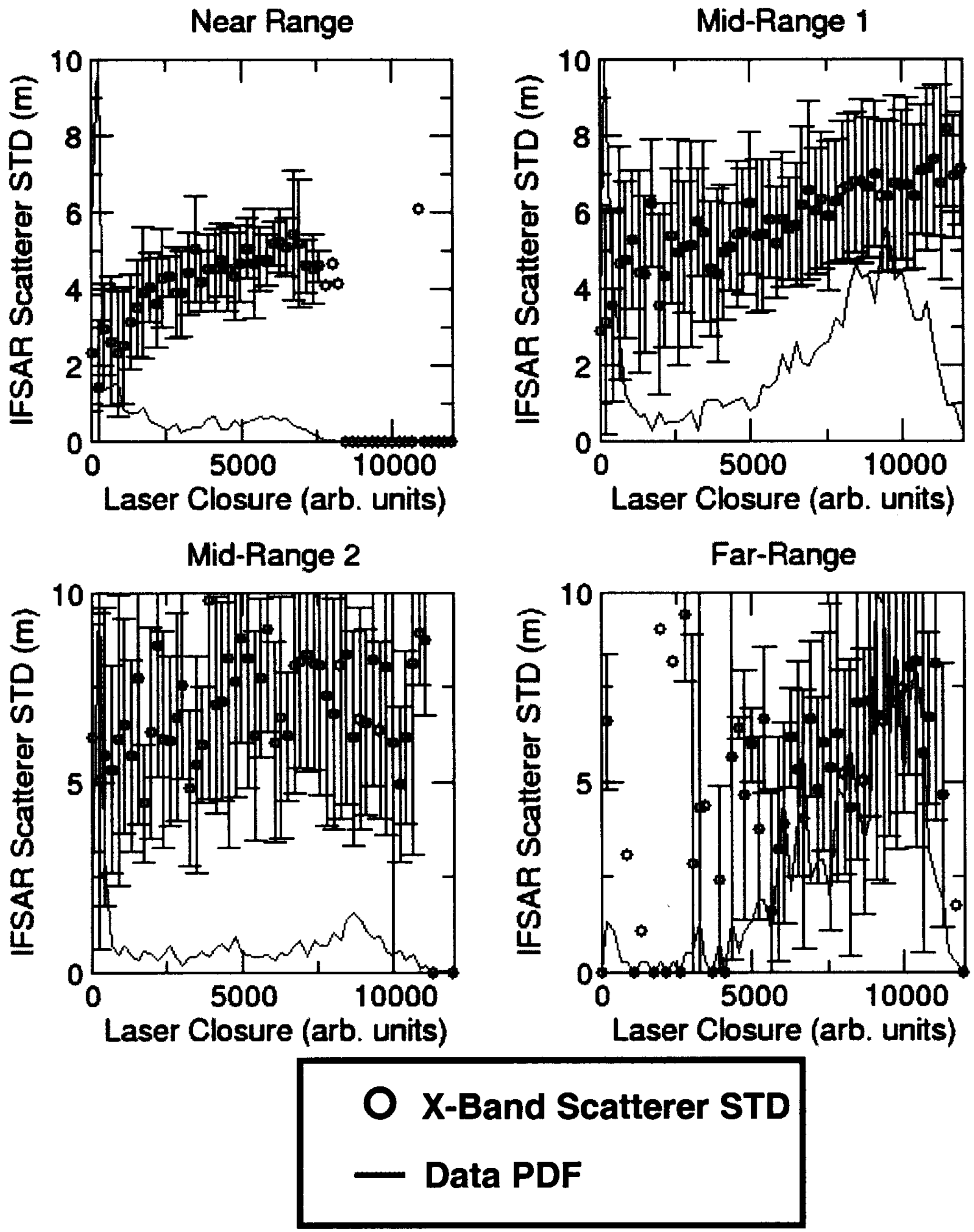


- The Laser Scatterer STD is computed by using the normalized laser waveform as the probability density function (pdf) to compute the height moments:

$$\left\langle z^n \right\rangle = \frac{\sum p_i z_i^n}{\sum p_i}$$

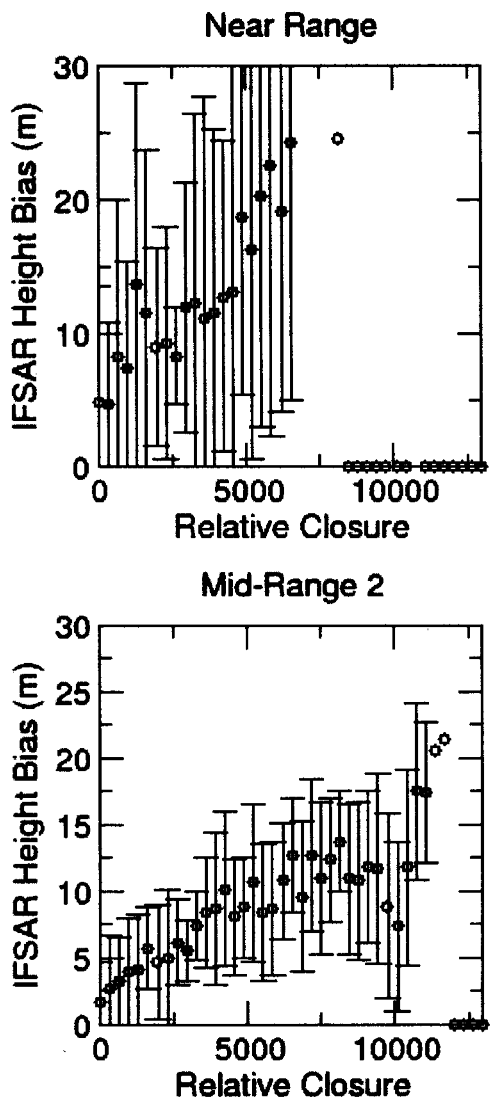
- The fact that the two STDs are well correlated indicates that at X-Band the penetration is governed by geometrical optics.
- The degradation of correlation with incidence angle may indicate a change in penetration (but residual calibration effects may also be present).

X-Band Scatterer STD vs Canopy Closure

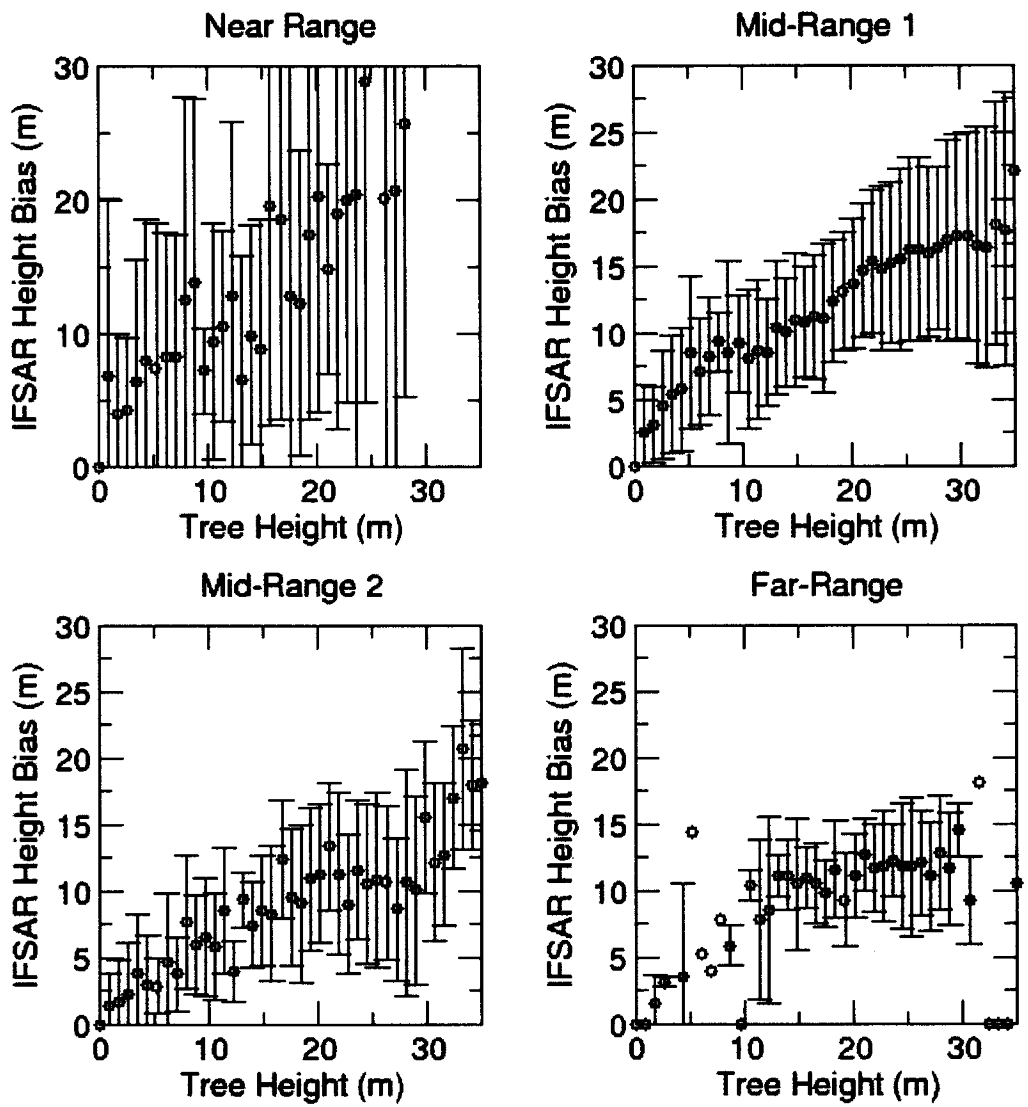


- Canopy closure is the fraction of the projected area shaded by canopy components.
- An estimate of the (relative) closure of the canopy can be obtained by integrating the waveform power from the canopy, and assuming that at any given height power is proportional to the area blocked by the canopy (assumes uniform canopy brightness).
- Canopy closure is an indicator of how much energy reaches the ground, and hence of penetration.
- There is a relationship between the X-band scatterer STD and closure, as expected, but the relationship is weaker than with the other parameters.
- Canopy closure is an independent variable from tree height which also determines the penetration. Studies using tree height and closure simultaneously are underway.

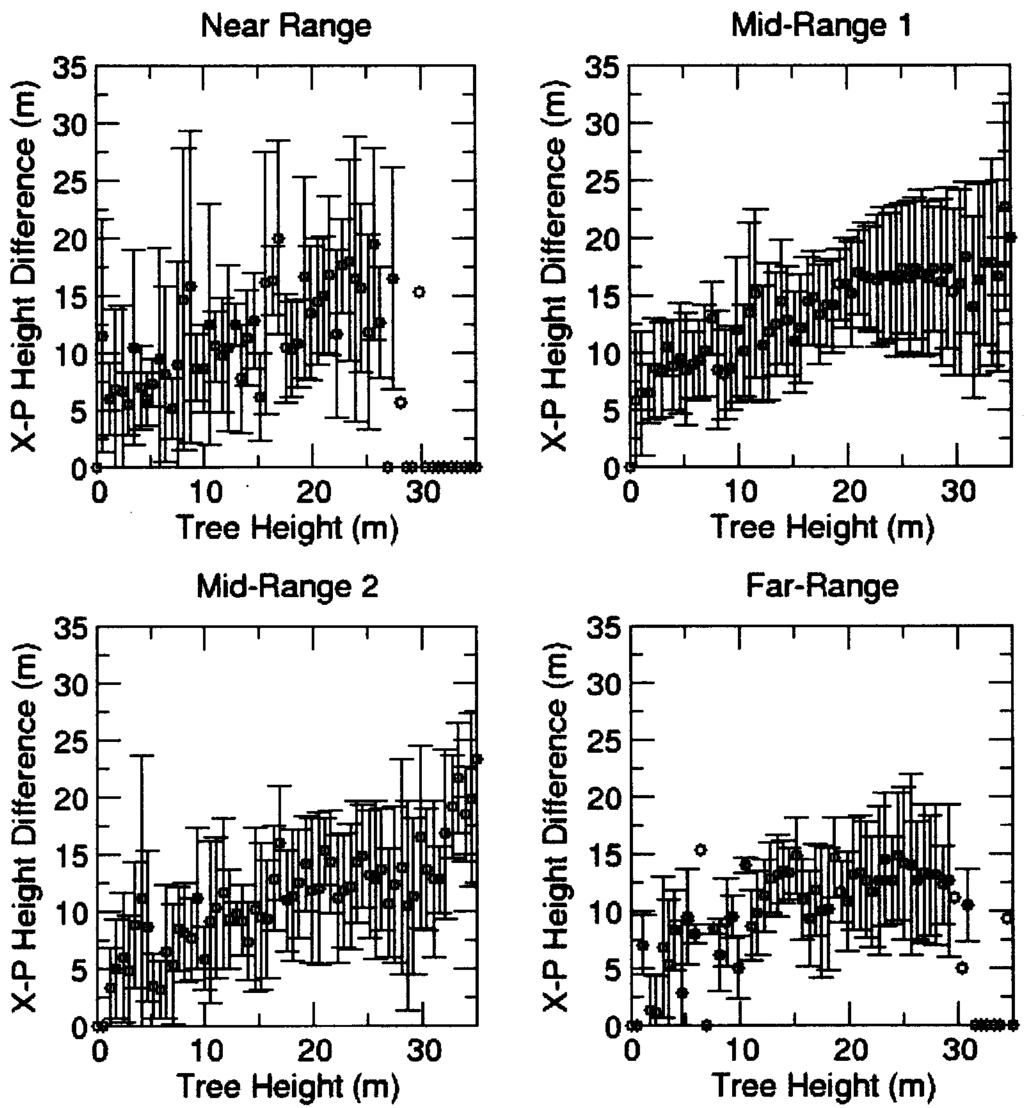
X-Band Height Bias vs Canopy Closure



Height Bias vs Tree Height

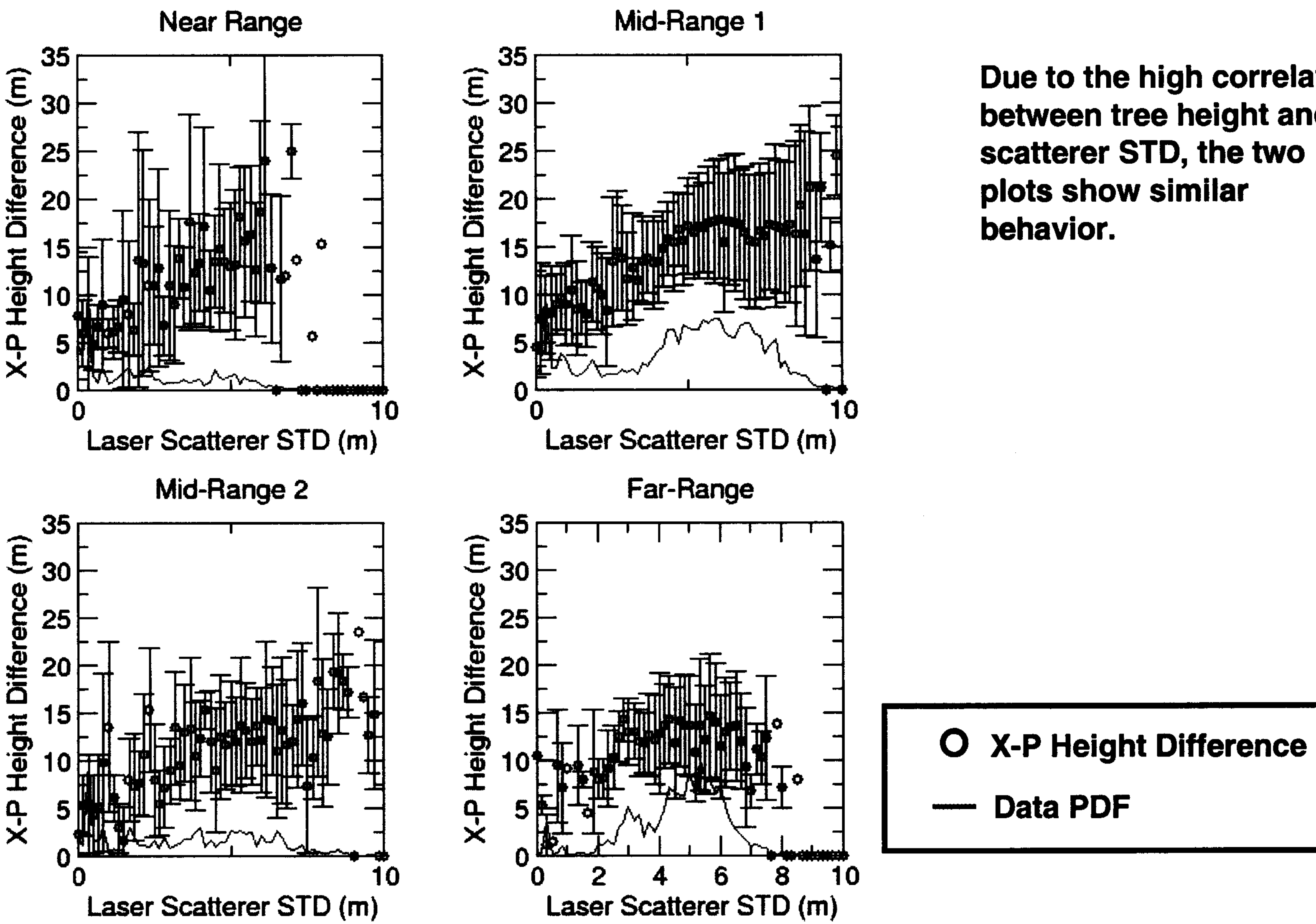


X-P Height Difference vs Tree Height



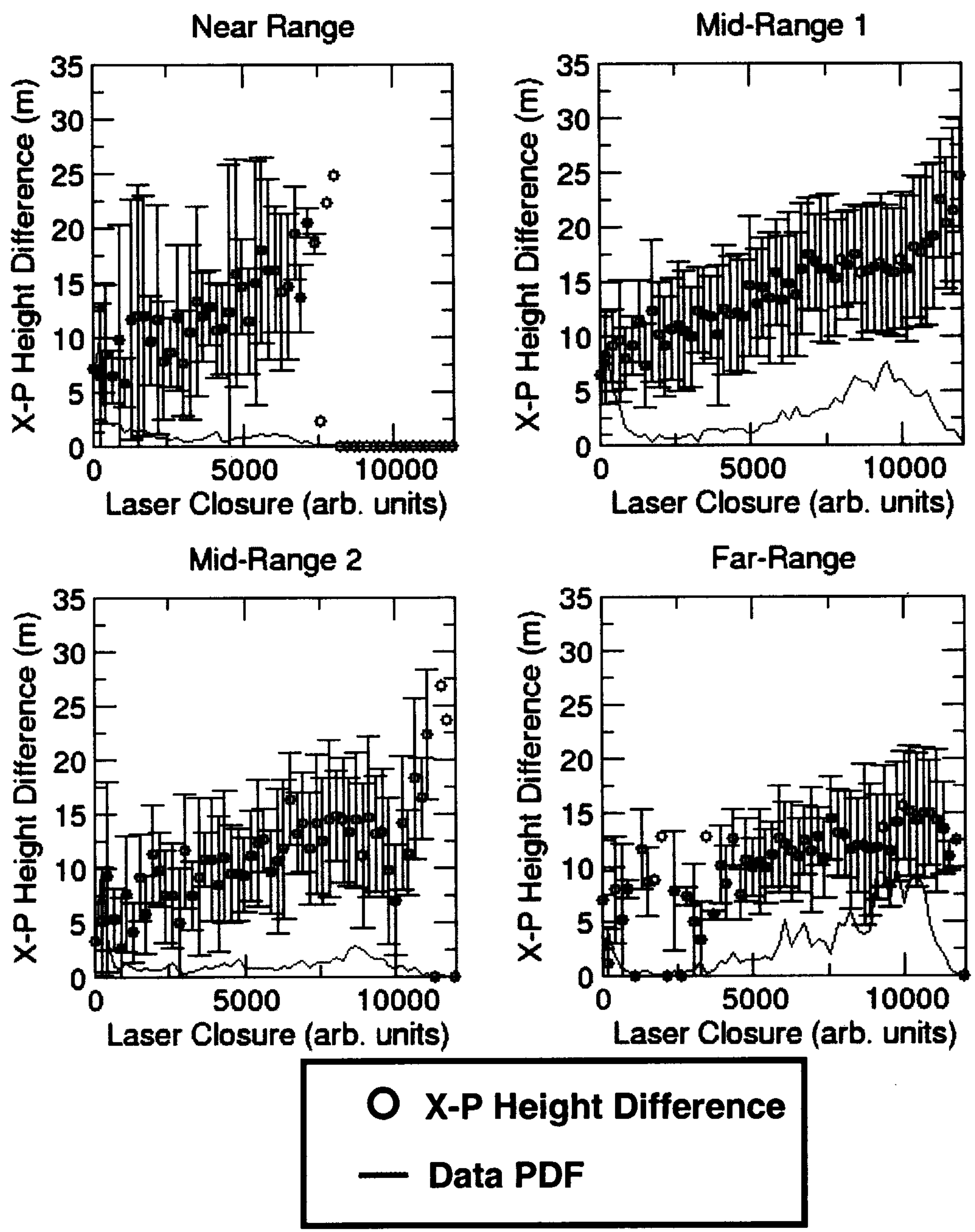
- In contrast to the scaterer STD, the X-P height difference has very similar behavior throughout the entire swath.
- However, in the first two subswaths, the scatterer STD is more correlated with tree height than the X-P height difference (see below).
- Notice that the X-P height difference is generally smaller than the tree height (specially for taller tress) indicating that either the X-Band penetrates significantly into the canopy, or the P-band is above the ground, or both.

X-P Height Difference vs Laser Scatterer STD



Due to the high correlation between tree height and scatterer STD, the two plots show similar behavior.

X-P Height Difference vs Canopy Closure



- The X-P height difference is slightly more correlated with canopy closure than with tree height.
- The correlation is only weakly dependent on incidence angle.
- These observations indicate that canopy closure may be a significant determinant of X-P height difference: the more closed a canopy is, the higher the X-band will be to the top of the canopy.